Long Baseline Neutrino Oscillation Experiment :

Sensitivities & Strategies

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Fermilab

DUSEL Workshop

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Outline

- The experimental questions and techniques
- Sensitivity Studies for Phase II experiments
- Conclusions drawn from these studies
- New Developments
  - Physics capability in a staged approach
  - Strategies for project development

Neutrino Mass and Mixing

Three neutrino flavors are related to three neutrino mass states by a mixing matrix :

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

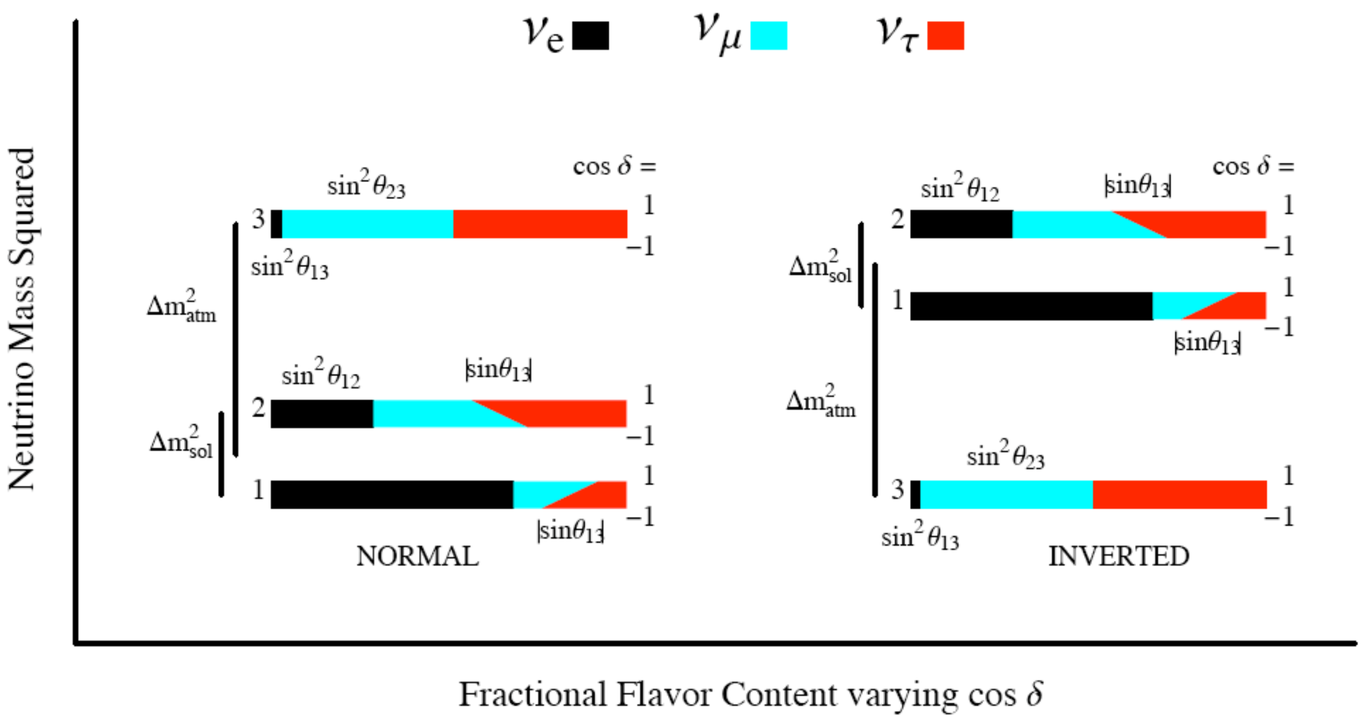
$$\left| \begin{matrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{matrix} \right\rangle = \begin{bmatrix} c\theta_{12} & s\theta_{12} & \\ -s\theta_{12} & c\theta_{12} & \\ & & 1 \end{bmatrix} \begin{bmatrix} c\theta_{13} & & s\theta_{13}e^{-i\delta} \\ & 1 & \\ -s\theta_{13}e^{i\delta} & & c\theta_{13} \end{bmatrix} \begin{bmatrix} 1 & & \\ & c\theta_{23} & s\theta_{23} \\ & -s\theta_{23} & c\theta_{23} \end{bmatrix} \left| \begin{matrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{matrix} \right\rangle$$

$P(\nu_e \rightarrow \nu_\mu) = \sin^2\theta_{12}\ \sin^2(1.27\Delta m^2_{12}L/E)$

$P(\nu_\mu \rightarrow \nu_\tau) = \sin^2\theta_{23}\ \sin^2(1.27\Delta m^2_{23}L/E)$

$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2\theta_{23}\ \sin^2 2\theta_{13}\ \sin^2(1.27\Delta m^2_{31}L/E)$

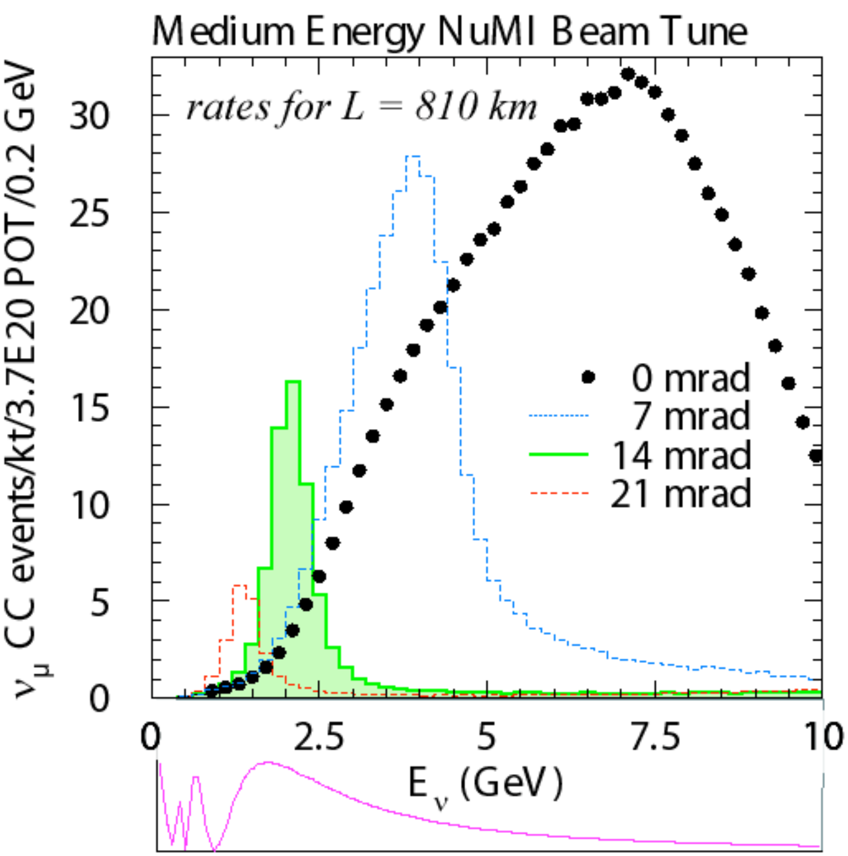
The Questions



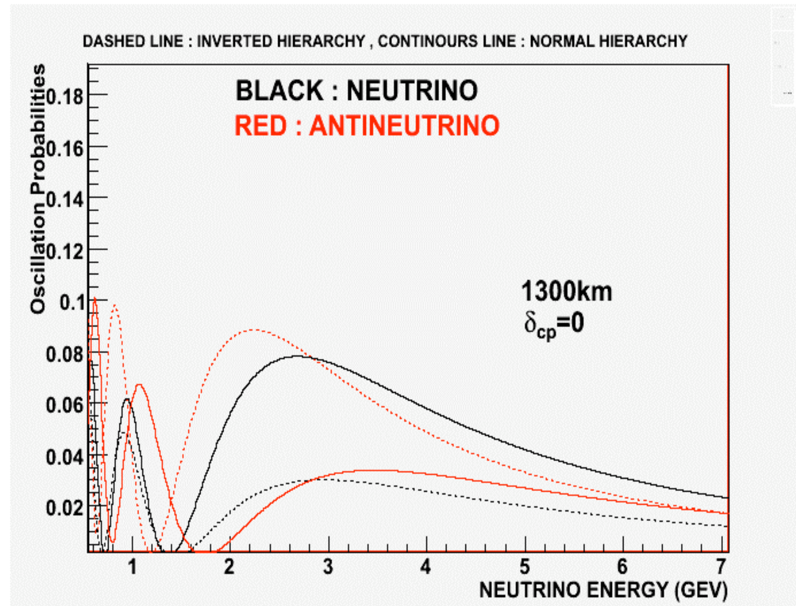
- What is the size of θ_{13}?
- Is the hierarch normal or inverted?
- What is the value of δ_{CP}?

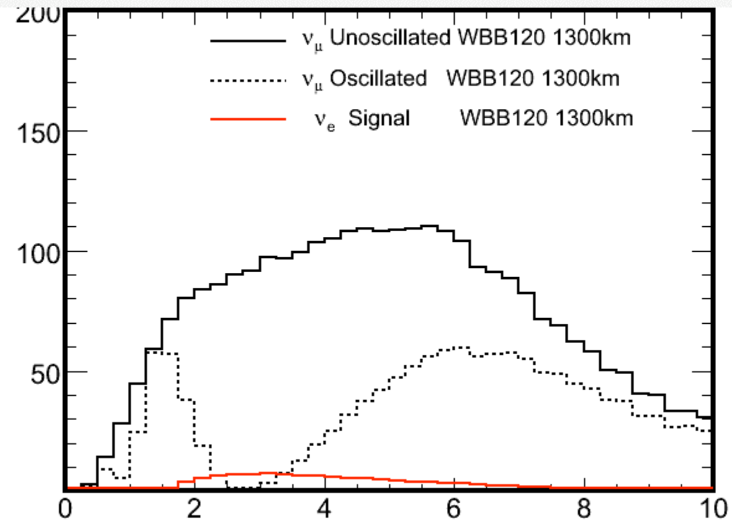
Experimental Techniques

Off-axis/narrow band beam

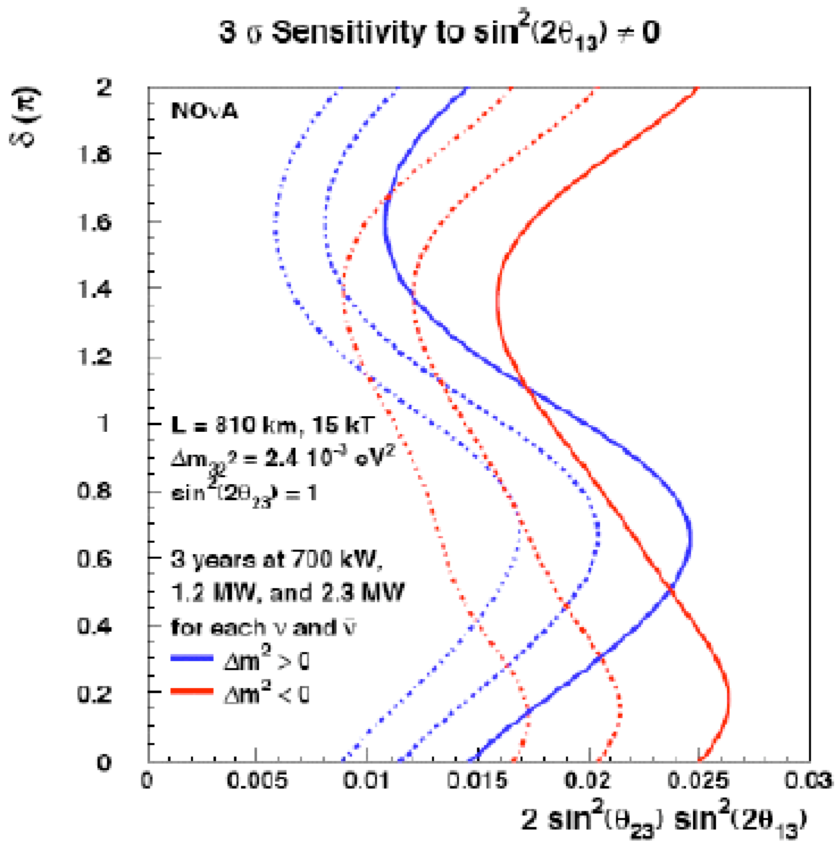


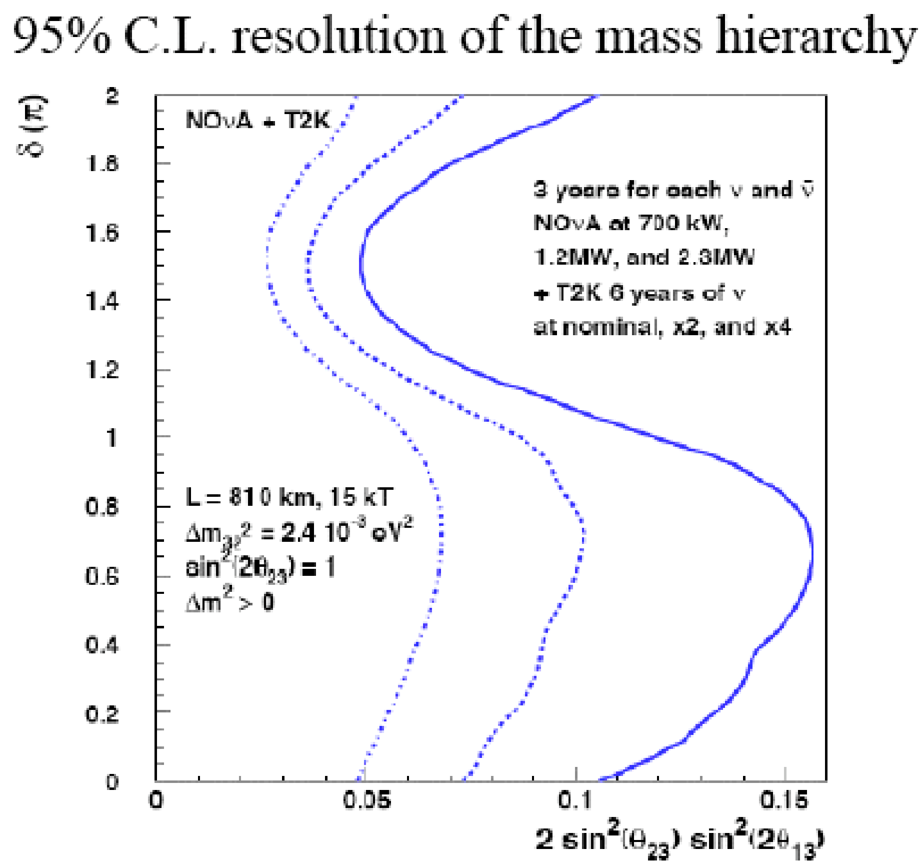
On-axis/wide band beam





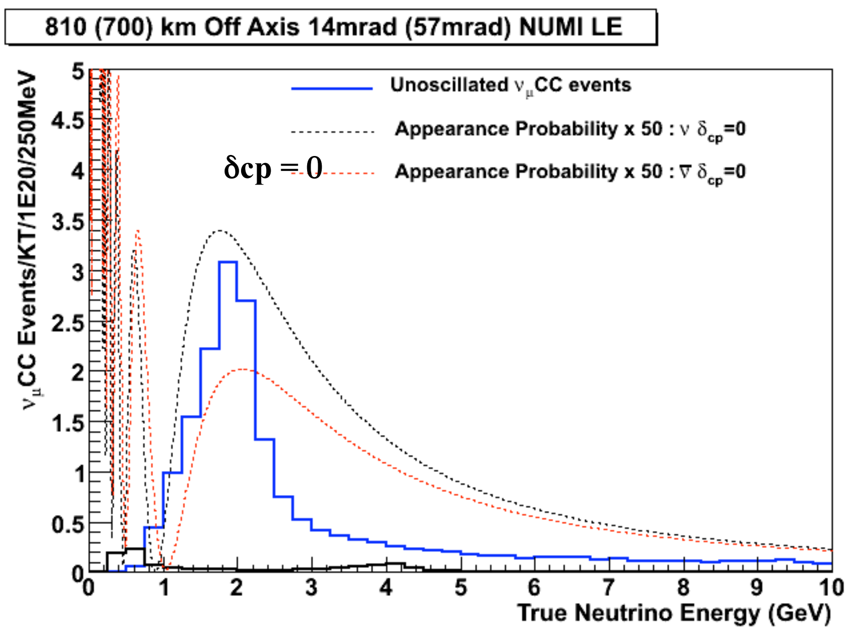
NOvA Experiment Sensitivities (shown by G.Feldman at P5 2008 SLAC meeting)

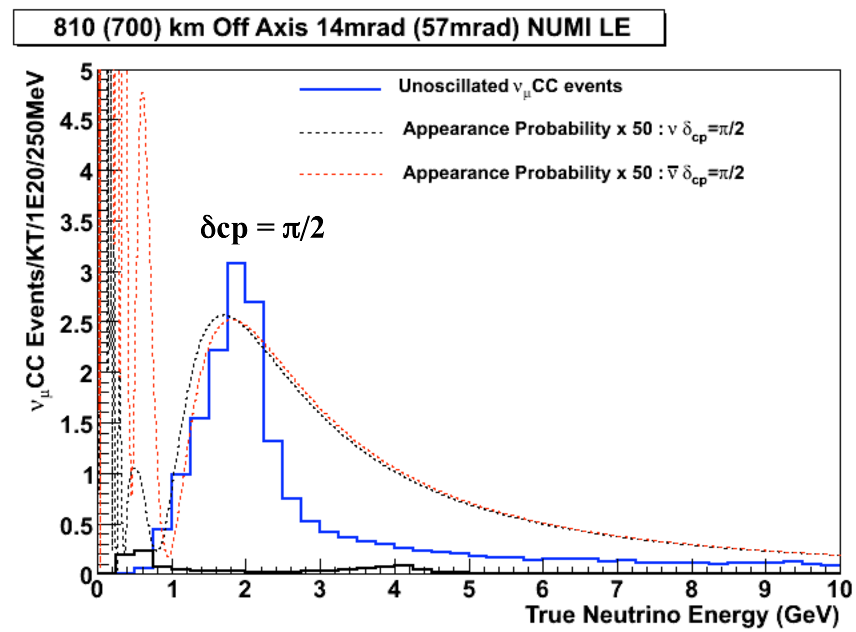




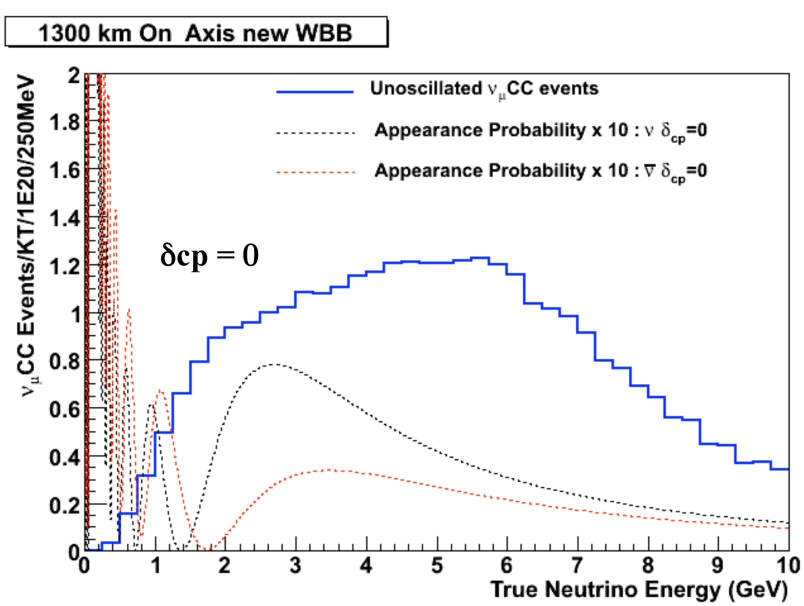
Normal Ordering

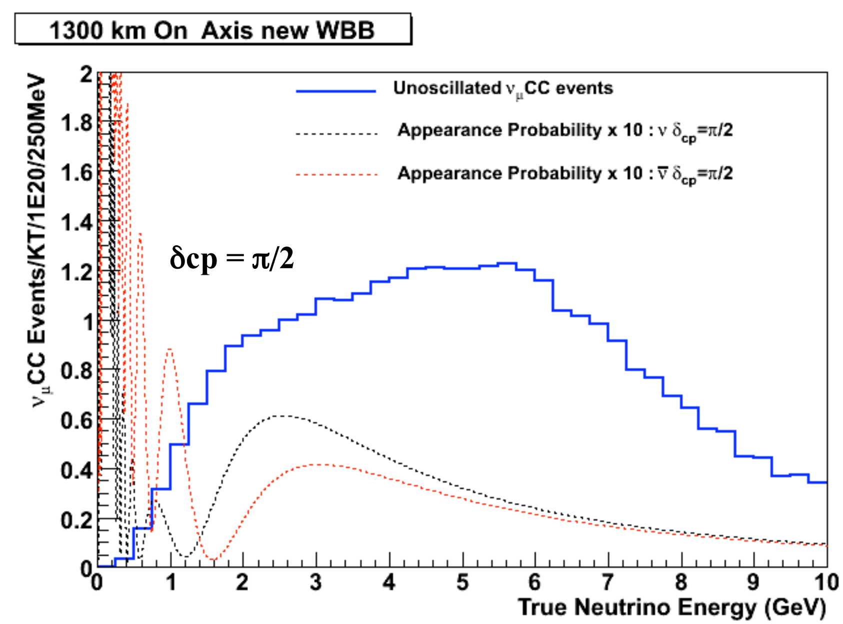
NuMI OFF AXIS : 1st and 2nd Oscillation Maxima 2 Detectors





ON AXIS WBB : 1st and 2nd Oscillation Maxima 1 Detector

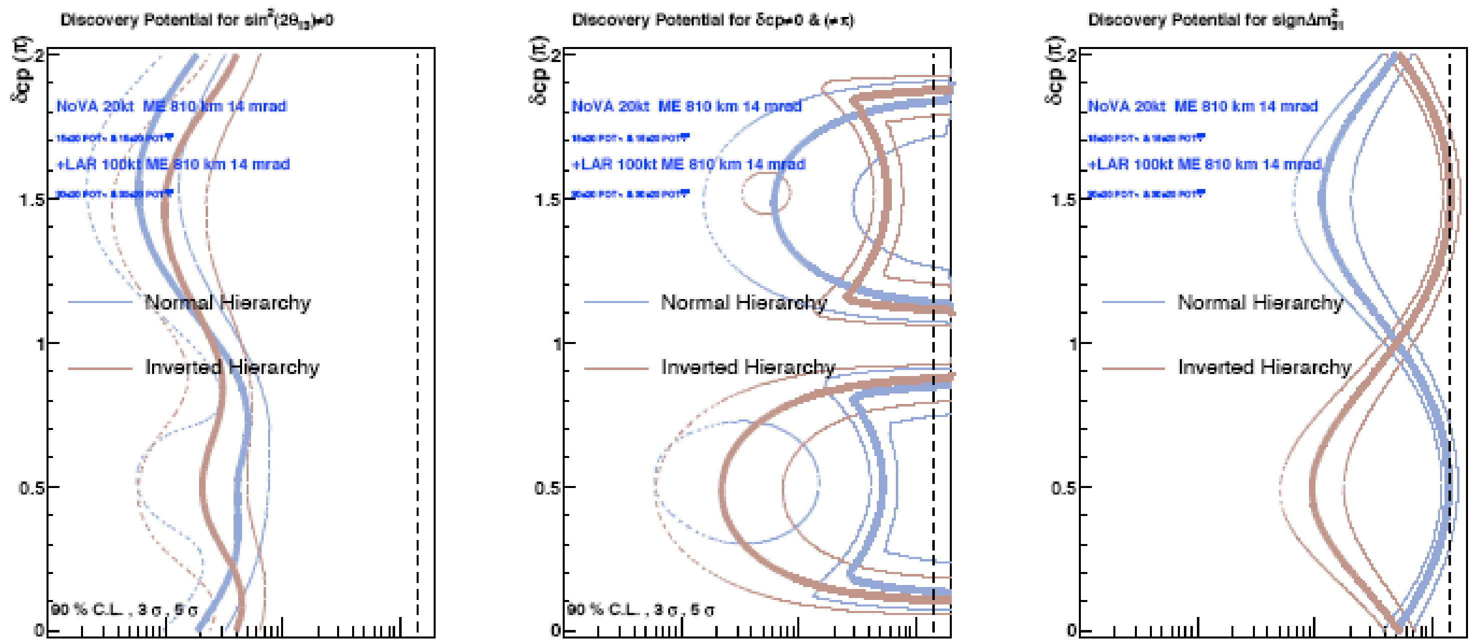




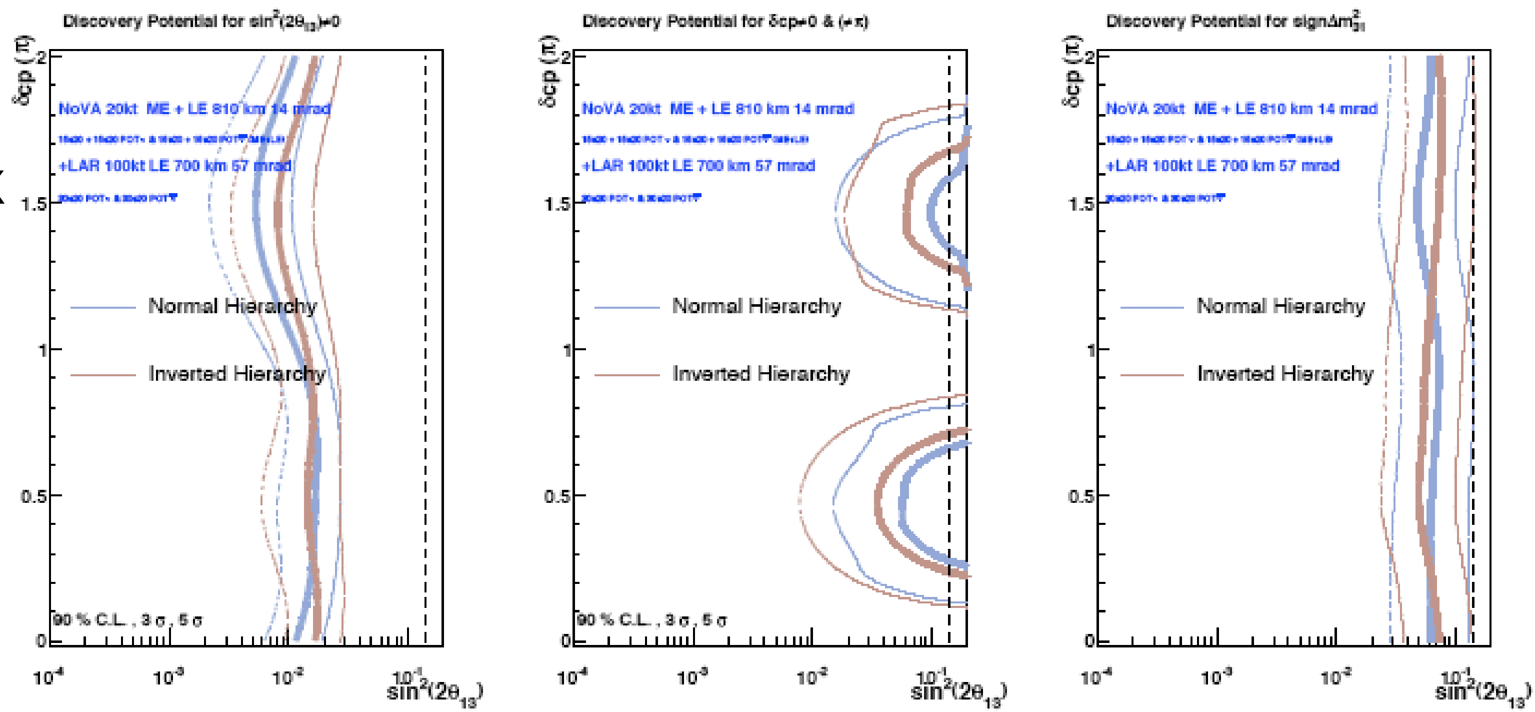
Neutrino Program Evolution

- Phase I : reactor experiments, T2K, NovA
- Numerous studies over the past several years have laid out options for the **next steps** in measuring the parameters of the neutrino mixing matrix
- i.e. BNL-FNAL US long baseline neutrino experiment study (March 2006-June 2007) explored
  - Beam options
    - NuMI , <u>new</u> Wide Band Beam to longer baseline
    - On and off axis detector locations
  - Detector technology options
    - Water cherenkov, liquid argon
- Several independent calculations of sensitivities give consistent results

NuMI 1st max

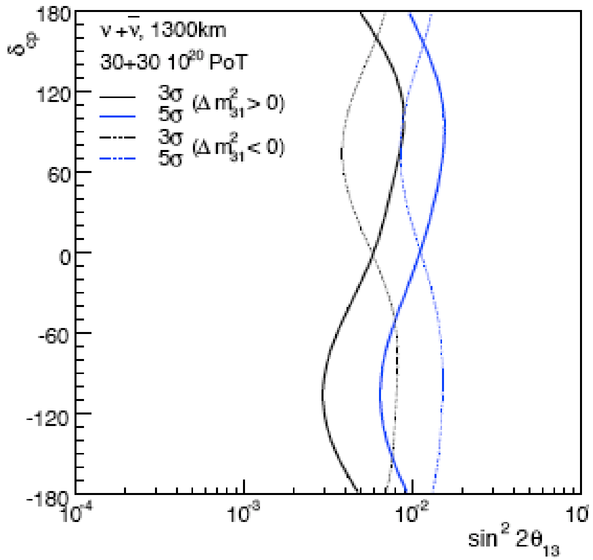


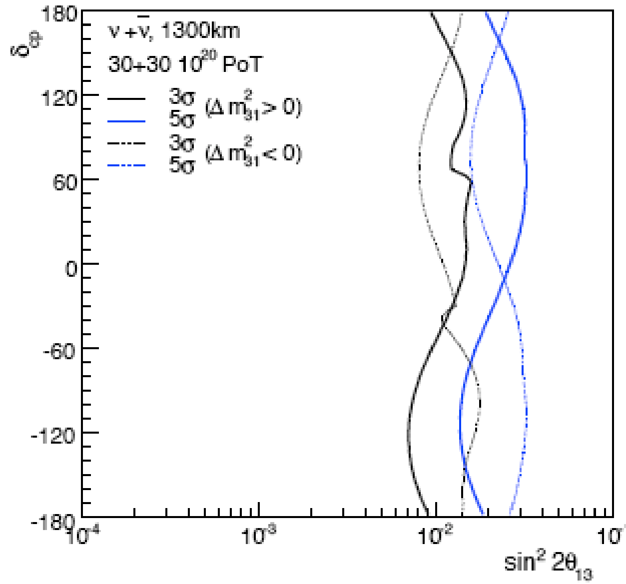
NuMI 2nd max

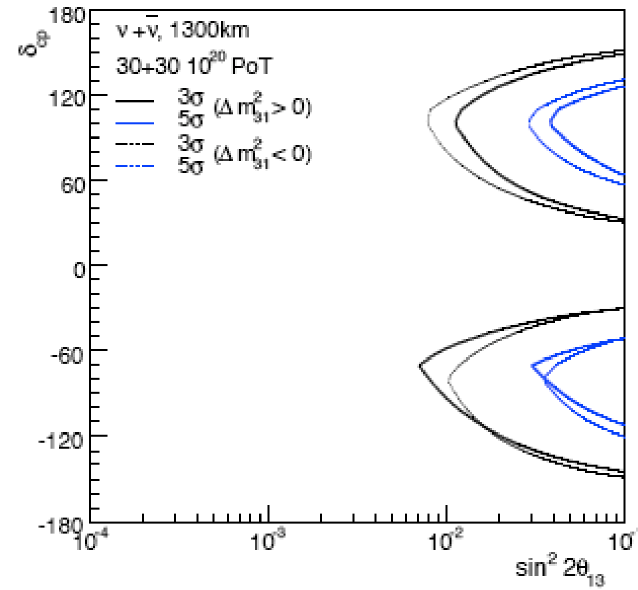


300 kT water cerenkov

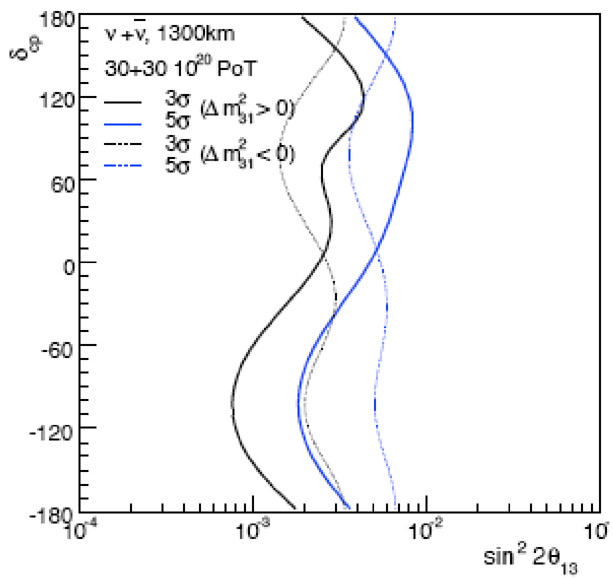
DUSEL baseline

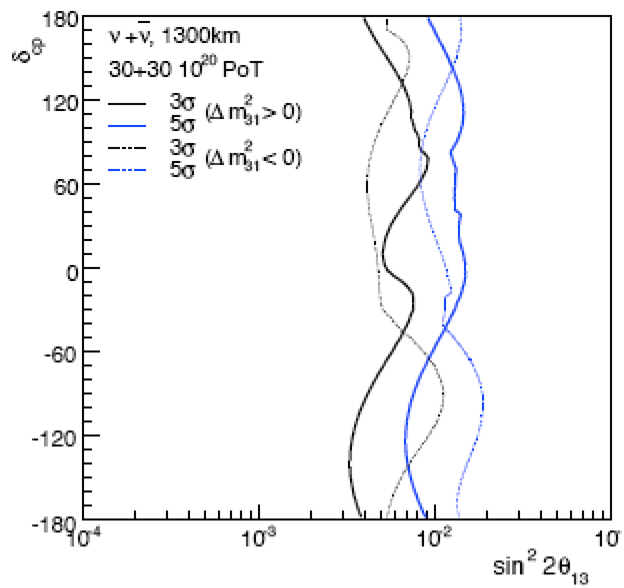


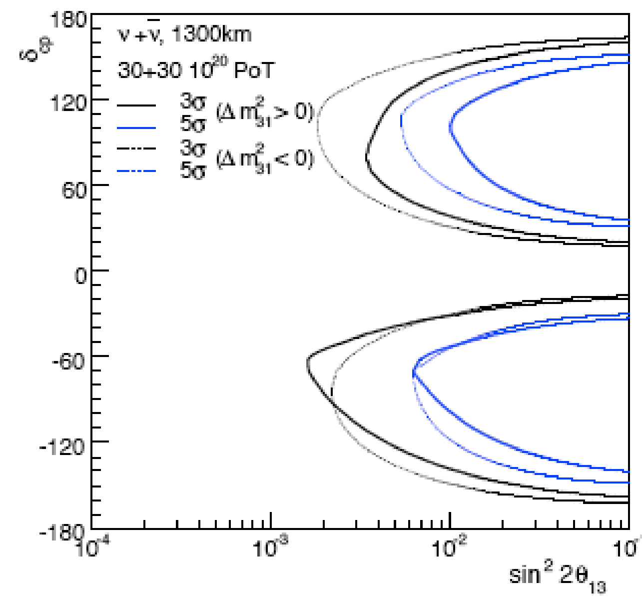




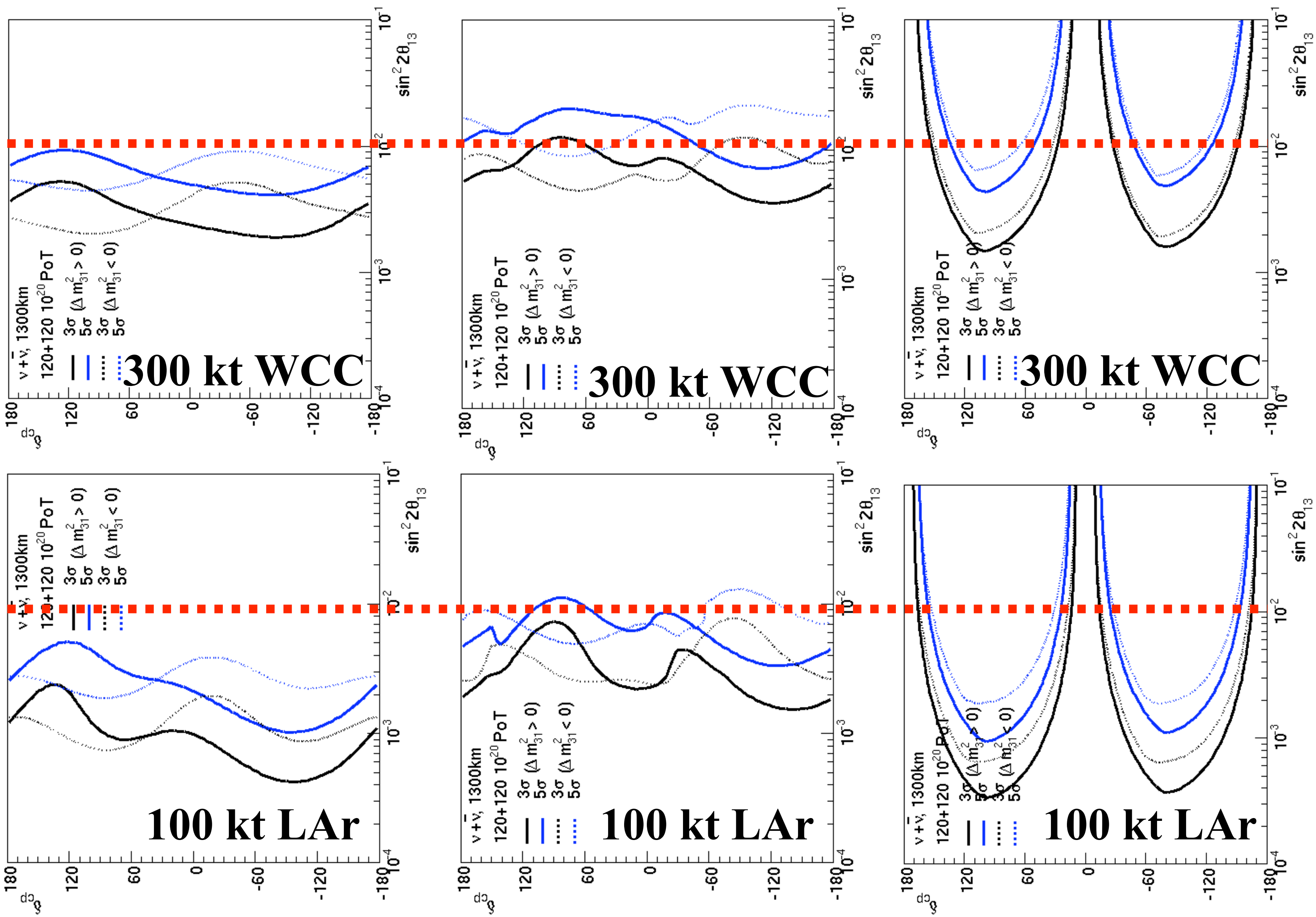
100 kT liquid argon







100 kt LAr vs 300 kt of WCC



From Peter Meyer's summary talk to P5, February 2008

30×10^{20} p.o.t neutrino + 30×10^{20} p.o.t antineutrino

≈ 3-5 years neutrino + 3-5 years antineutrino

Option	$\sin^2 2\theta_{13}$ 3σ,50% δ_{CP}	CPV 3σ,50% δ_{CP}	$\text{sgn}(\Delta m^2_{13})$ 3σ,50% δ_{CP}
1) NuMI-ME 0.9° 100 kt LAr, 1st max	0.002	0.02	0.05
2) NuMI-LE 0.9°/3.3° 50/50 kt LAr, 1st/2nd max	0.004	0.05	0.04
3) WBB 0.5° 300 kt H_2O Ch, 1300 km	0.006	0.02	0.01
4) WBB 0.5° 100 kt LAr, 1300 km	0.002	0.005	0.006

Entries are minimum $\sin^2 2\theta_{13}$ where null hypothesis is ruled out

From Peter Meyer's summary talk to P5, February 2008

30×10^{20} p.o.t neutrino + 30×10^{20} p.o.t antineutrino
≈ 3-5 years neutrino + 3-5 years antineutrino @ 1 MW

Option	$\sin^2 2\theta_{13}$ 5σ, all δ_{CP}	CPV 5σ,50% δ_{CP}	$\mathrm{sgn}(\Delta m^2_{13})$ 5σ, all δ_{CP}
1) NuMI-ME 0.9° 100 kt LAr, 1st max	0.008	0.08	0.18
2) NuMI-LE 0.9°/3.3° 50/50 kt LAr, 1st/2nd max	0.011	>0.10	0.15
3) WBB 0.5° 300 kt H_2O Ch, 1300 km	0.015	>0.10	0.032
4) WBB 0.5° 100 kt LAr, 1300 km	0.008	0.035	0.019

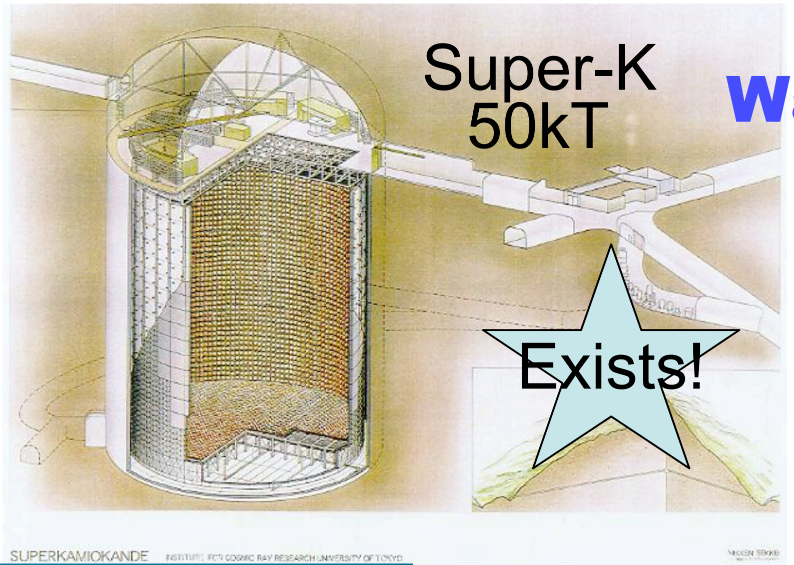
Entries are minimum $\sin^2 2\theta_{13}$ where null hypothesis is ruled out

From Peter Meyer's summary talk to P5, February 2008

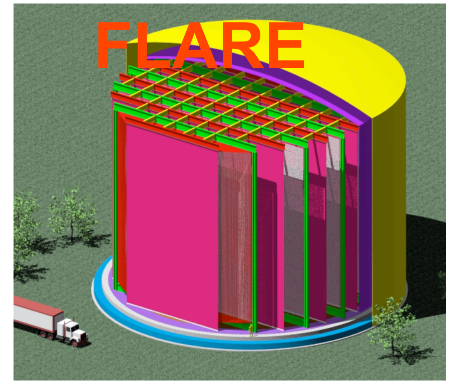
Option	$\sin^2 2\theta_{13}$ 5σ, all δ_{CP}	CPV 5σ,50% δ_{CP}	$\mathrm{sgn}(\Delta m^2_{13})$ 5σ, all δ_{CP}
1) NuMI-ME 0.9° 100 kt LAr, 1st max	0.008	0.08	0.18
2) NuMI-LE 0.9°/3.3° 50/50 kt LAr, 1st/2nd max	0.011	>0.10	0.15
2A) 100/100 kt LAr	0.009	0.08	0.08
3) WBB 0.5° 300 kt H_2O Ch, 1300 km	0.015	>0.10	0.032
3A) 60×10^{20} p.o.t. each	0.012	0.08	0.022
4) WBB 0.5° 100 kt LAr, 1300 km	0.008	0.035	0.019

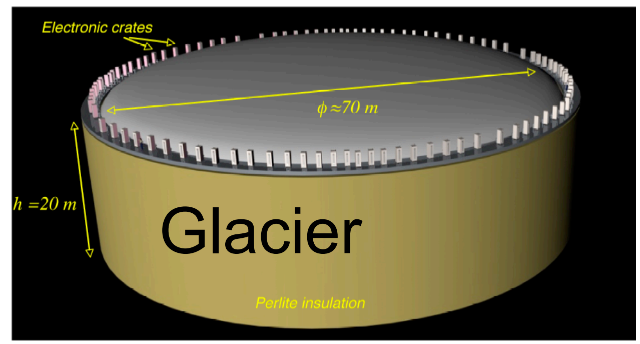
Entries are minimum $\sin^2 2\theta_{13}$ where null hypothesis is ruled out

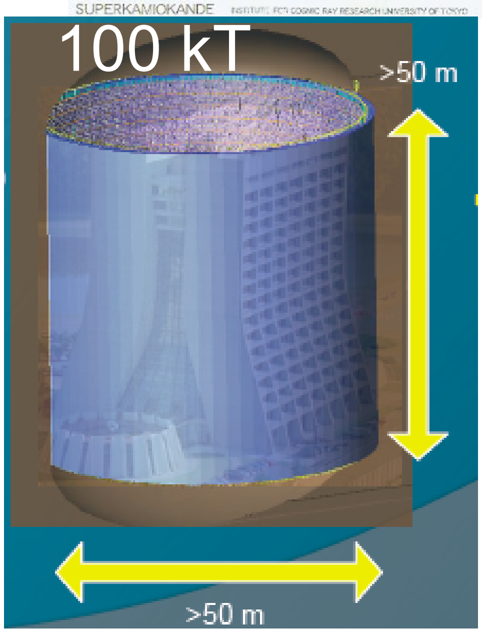
Large Detector Concepts

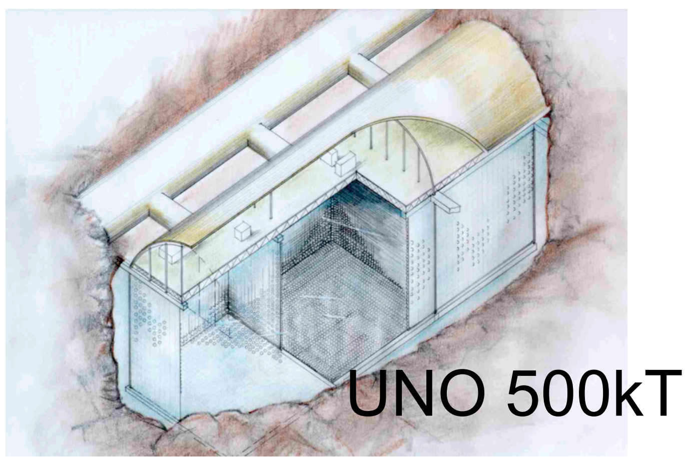


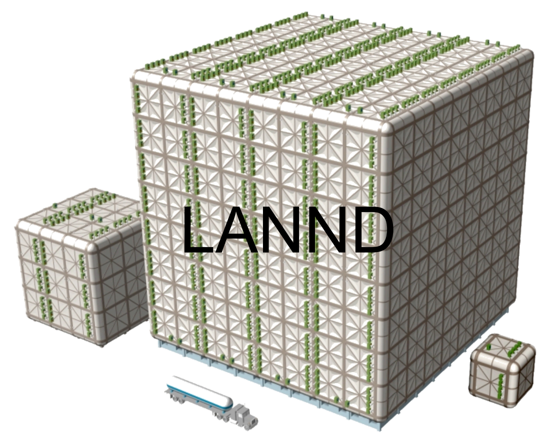
Water Cerenkov
And
Liquid Argon



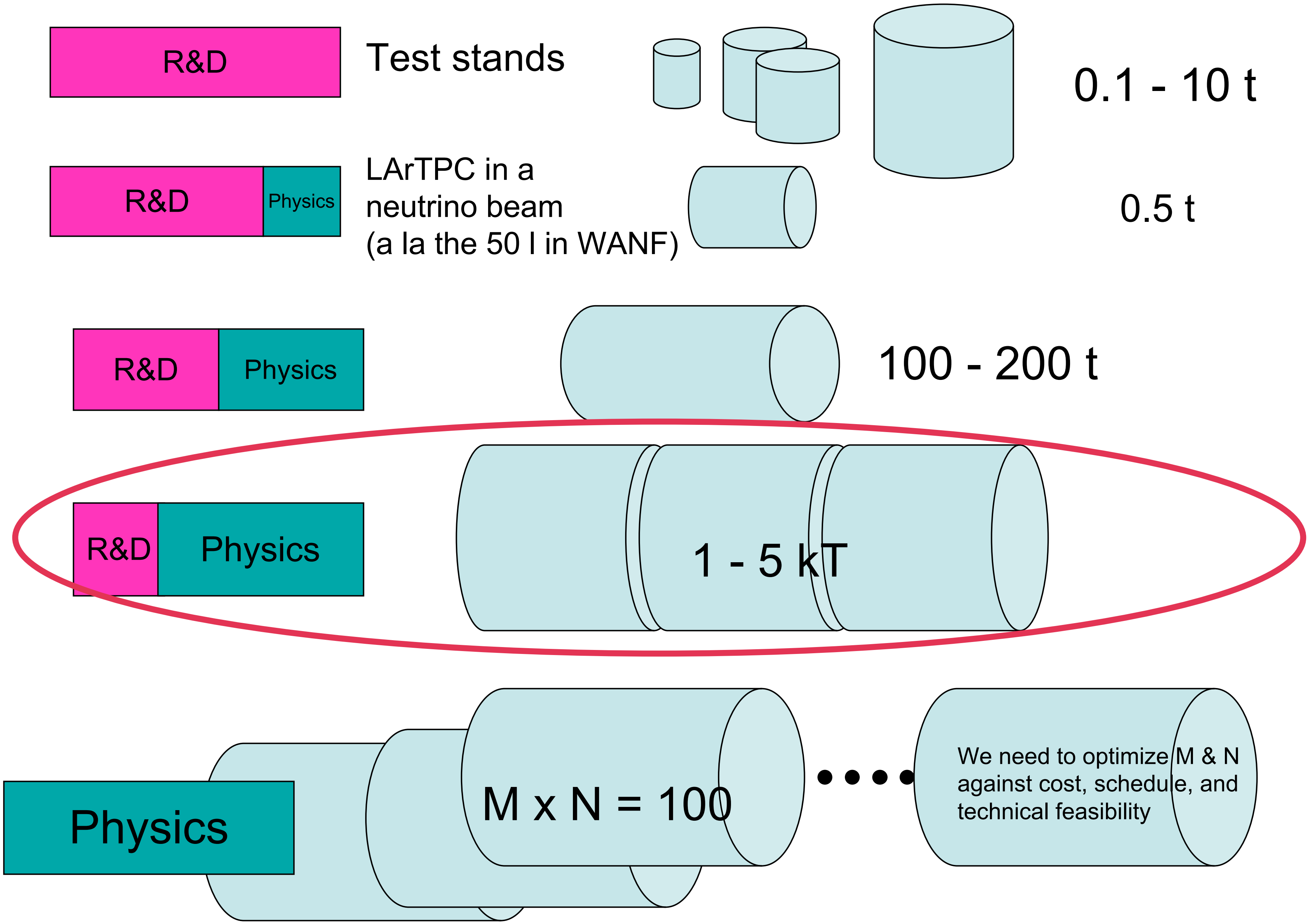




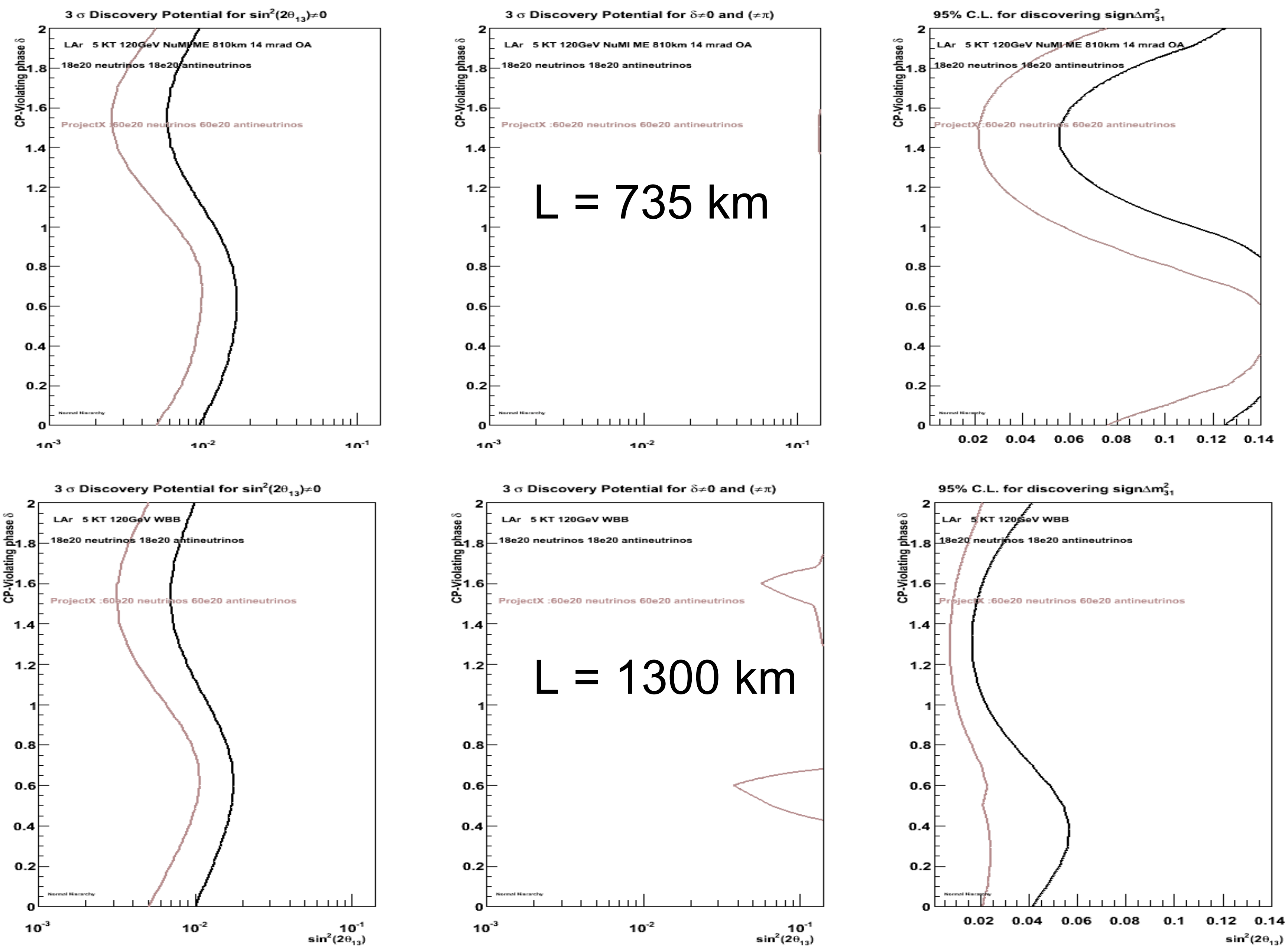




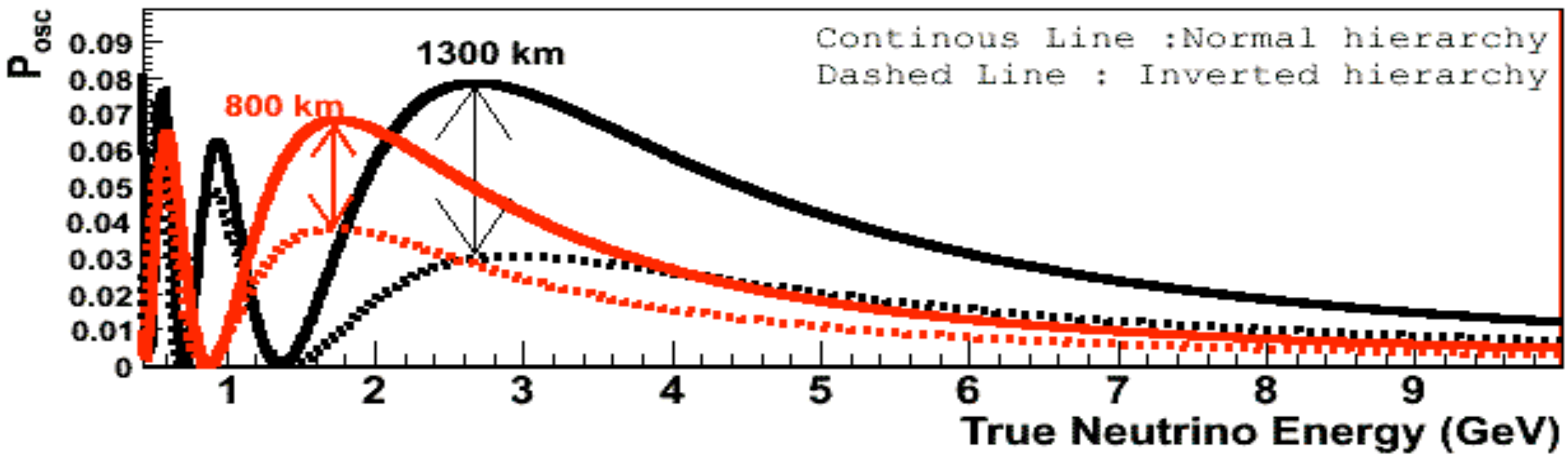
Evolution of a Liquid Argon Physics Program



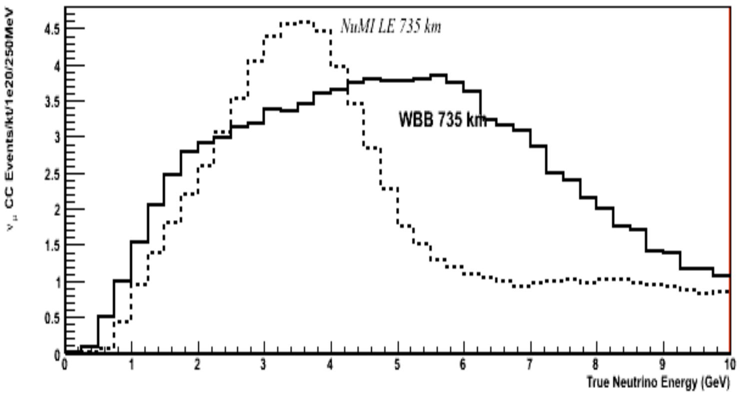
Options for Liquid Argon 5 kT

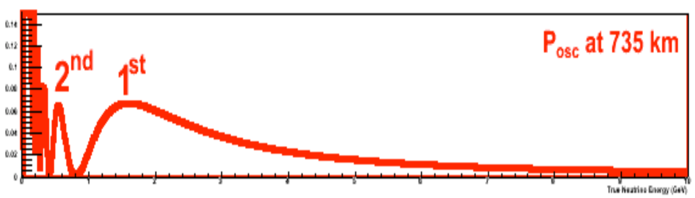


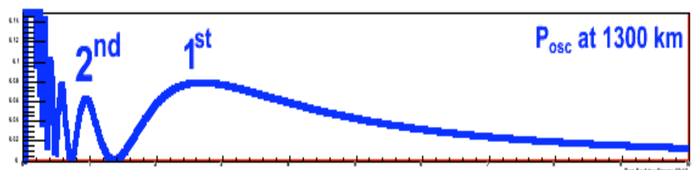
Why is the longer baseline so much better?

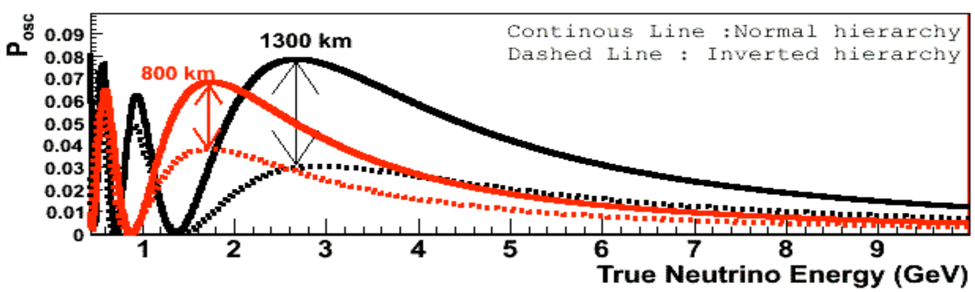


The effect of longer baseline (>>L) and a new Wide Band Beam









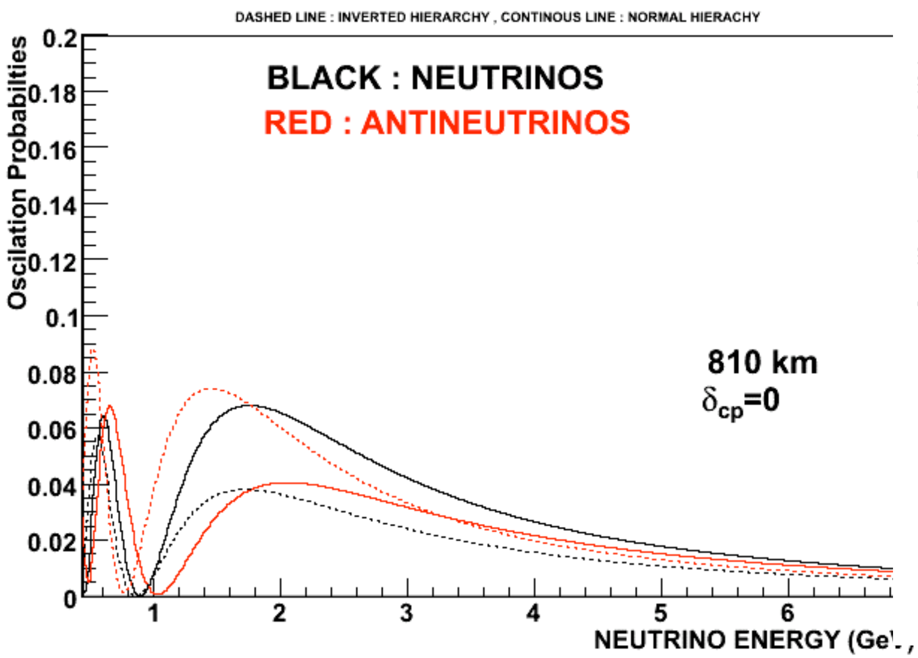
With new Wide Band Beam :

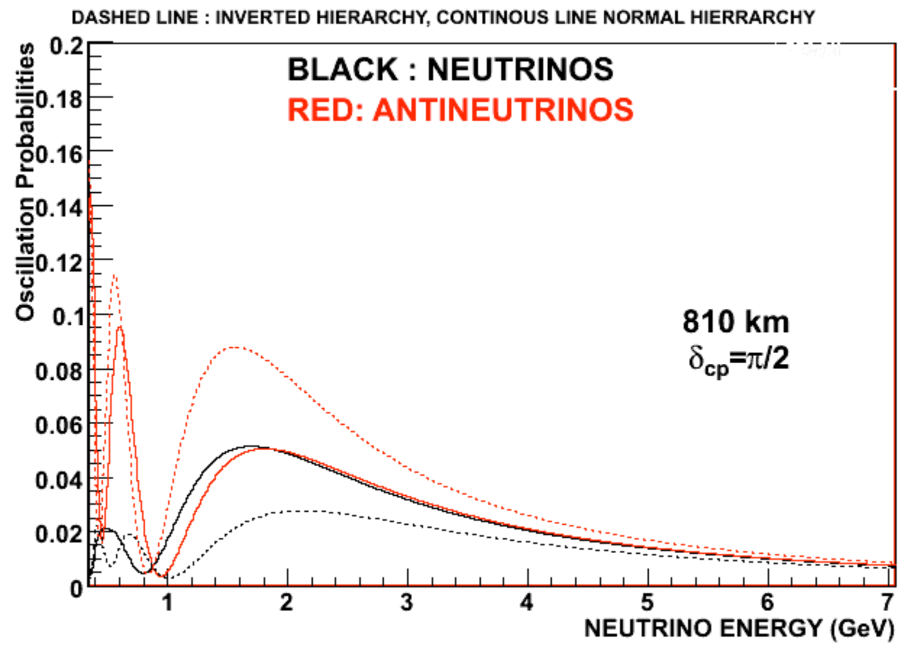
Increase "useful" flux (at first and second oscillation maxima)

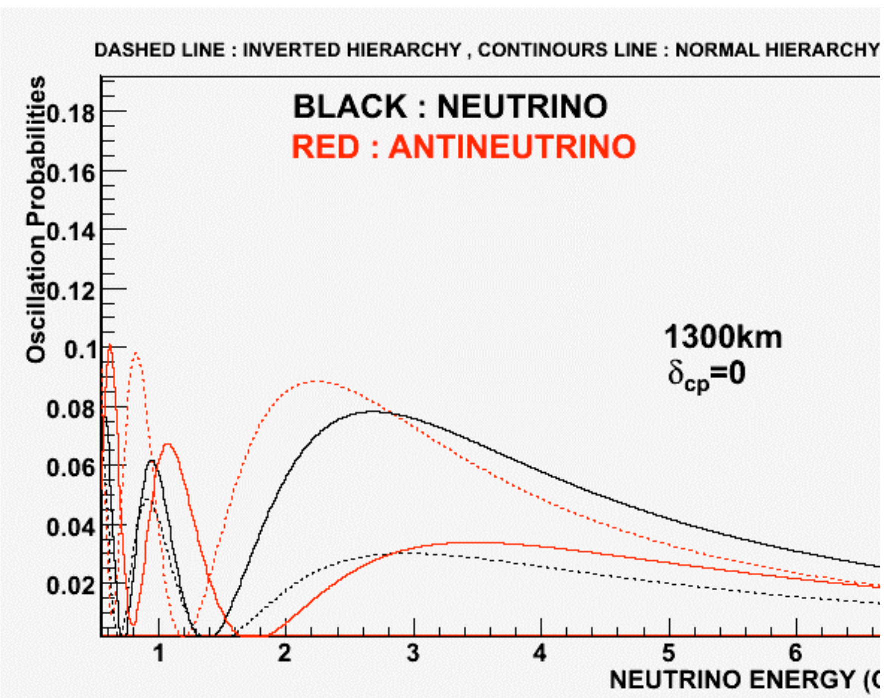
Decrease backgrounds (depending on proton energy and off axis angle)

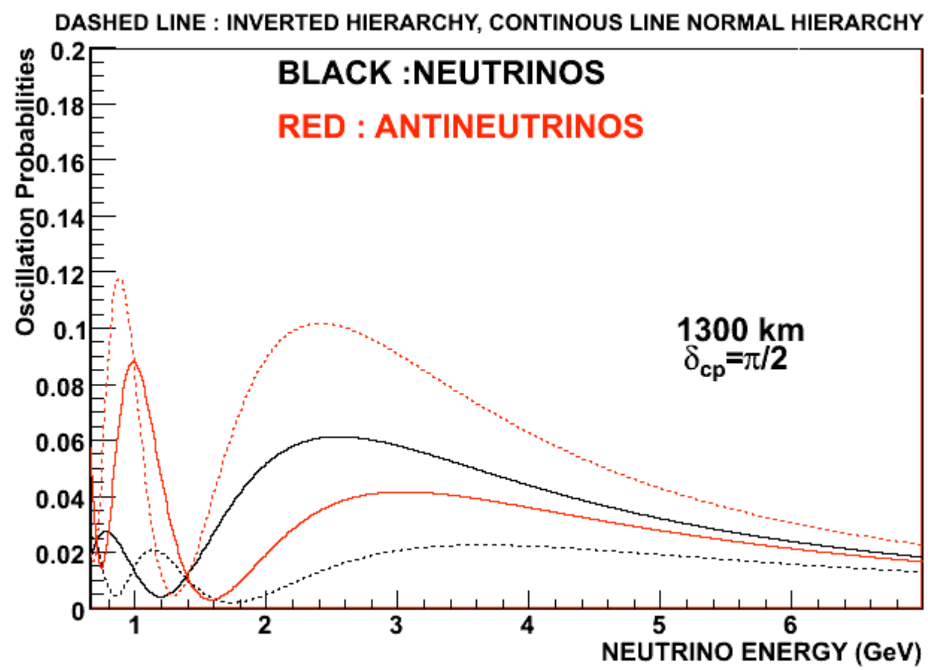
With increasing L oscillation maxima (and minima) "appear" in more "favourable" positions in the neutrino energy spectra

With increasing L matter effects increase and hence mass hierarchy determination is improving


DASHED LINE : INVERTED HIERARCHY , CONTINOUS LINE : NORMAL HIERACHY
BLACK : NEUTRINOS
RED : ANTINEUTRINOS
810 km
δ_{cp}=0
Oscillation Probabilities
NEUTRINO ENERGY (GeV)


DASHED LINE : INVERTED HIERARCHY, CONTINOUS LINE NORMAL HIERRARCHY
BLACK : NEUTRINOS
RED: ANTINEUTRINOS
810 km
δ_{cp}=π/2
Oscillation Probabilities
NEUTRINO ENERGY (GeV)


DASHED LINE : INVERTED HIERARCHY , CONTINOURS LINE : NORMAL HIERARCHY
BLACK : NEUTRINO
RED : ANTINEUTRINO
1300km
δ_{cp}=0
Oscillation Probabilities
NEUTRINO ENERGY (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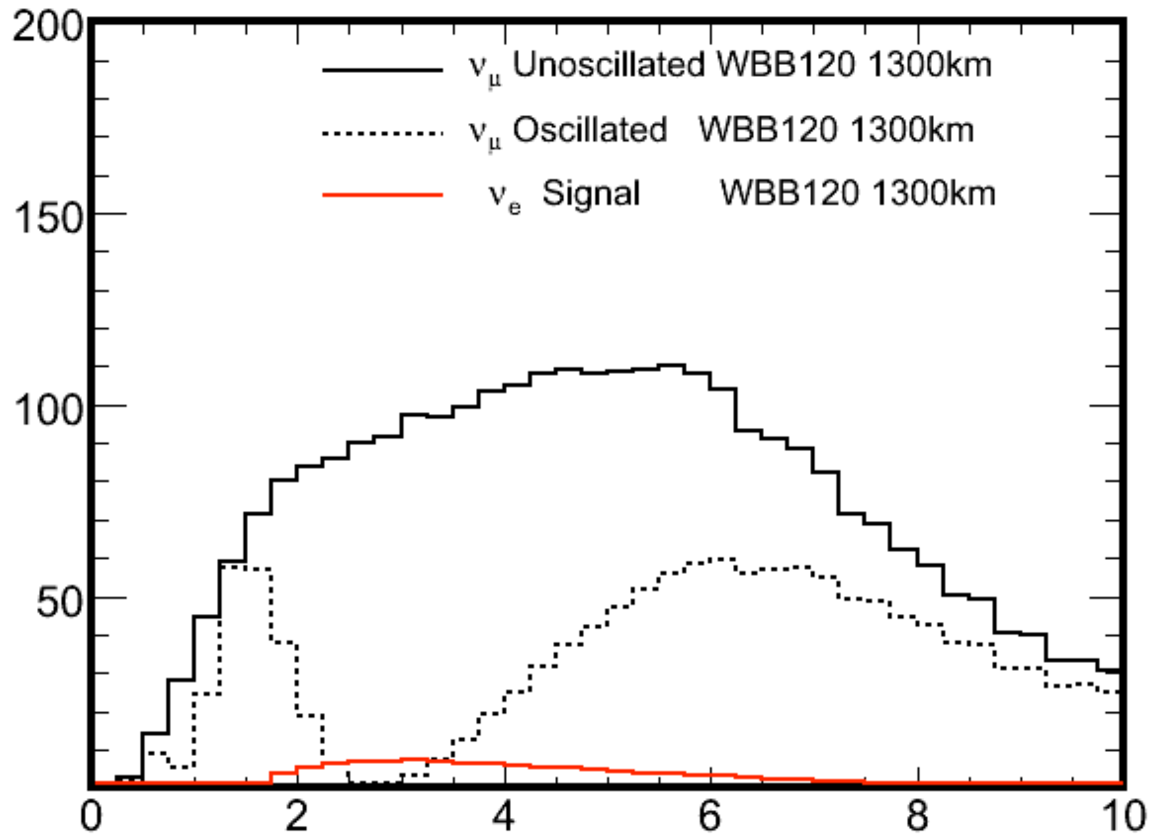
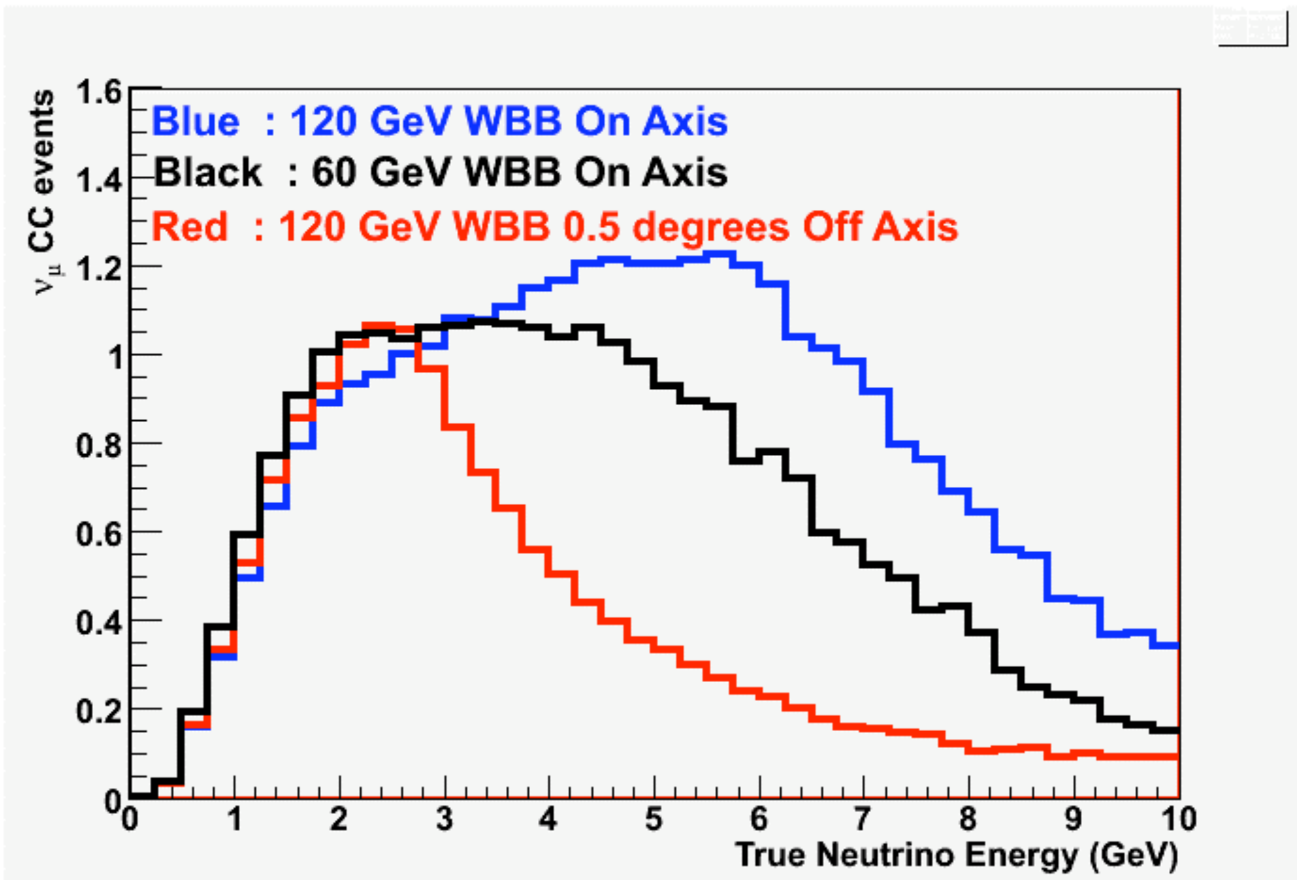


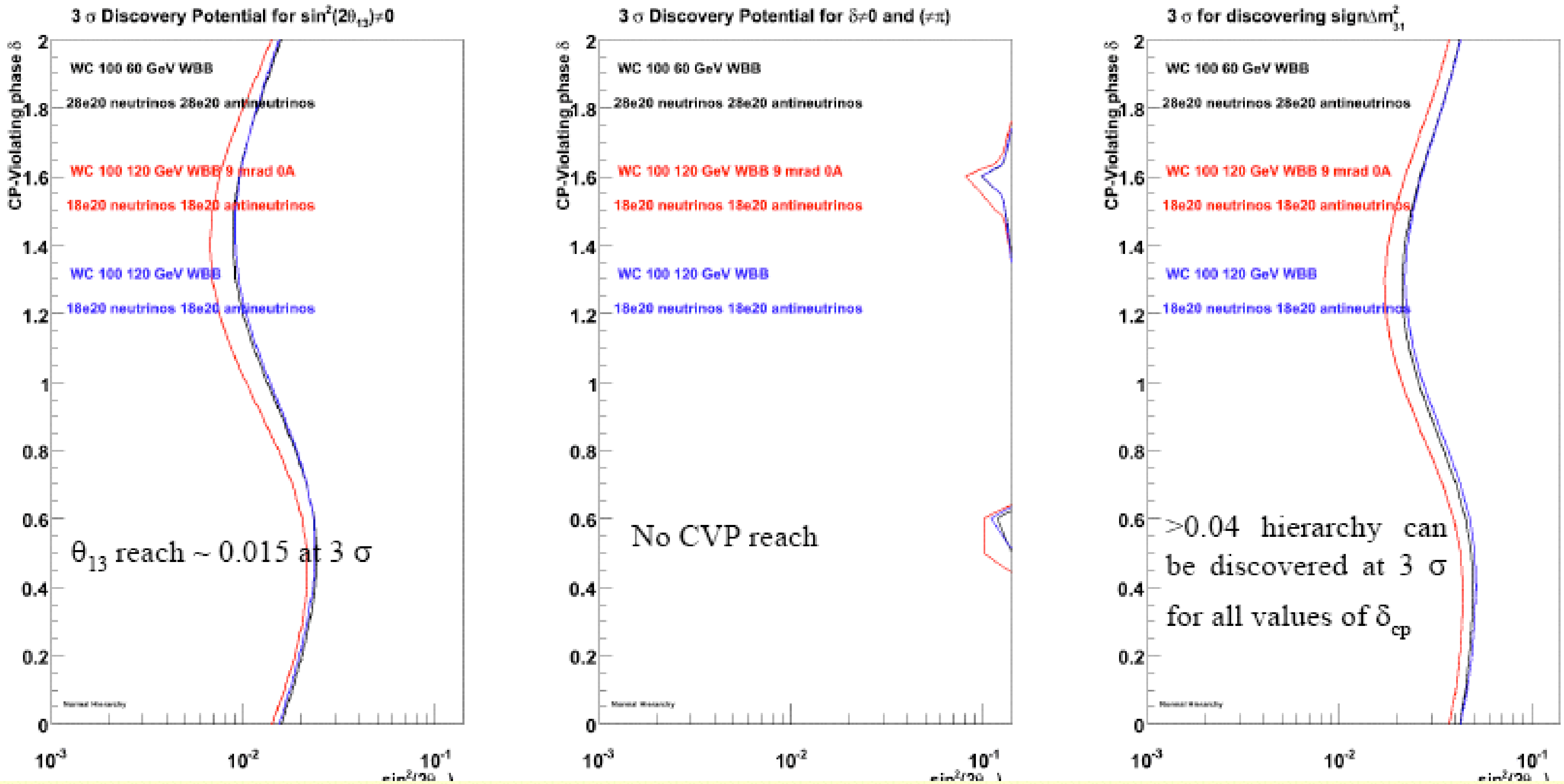
ν_μ Unoscillated WBB120 1300km
ν_μ Oscillated WBB120 1300km
ν_e Signal WBB120 1300km
200
150
100
50
0
2
4
6
8
10

Options and optimizations



Sensitivities for 100kt fiducial Water Cherenkov

"Nominal" NC background

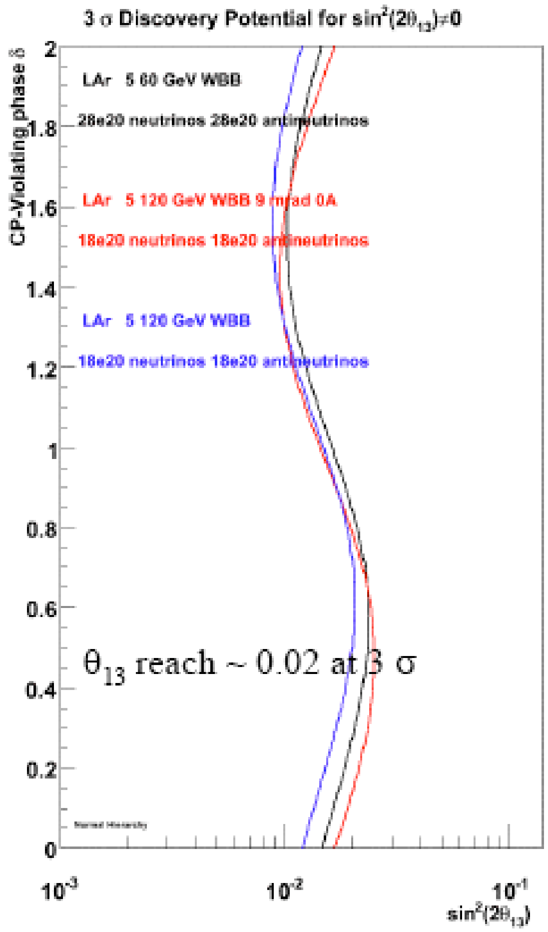


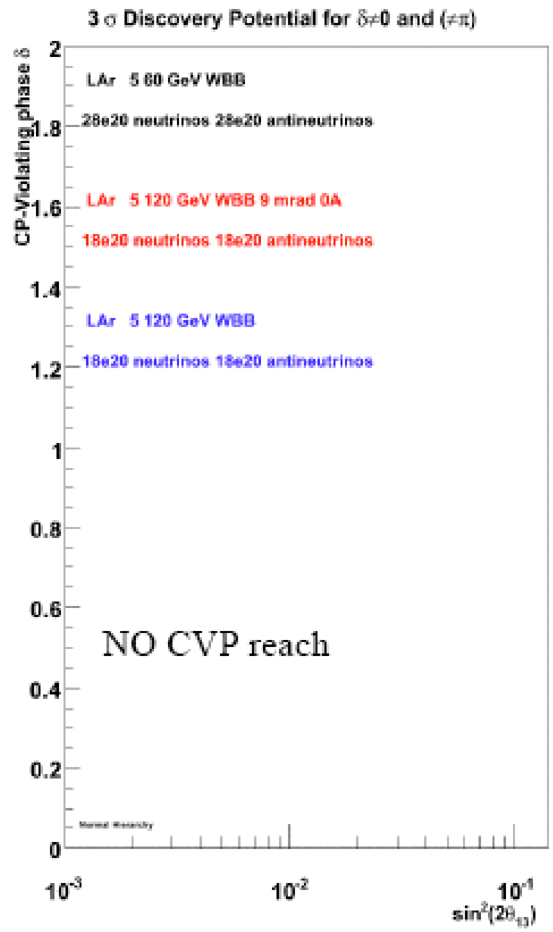
120 GeV 700 KW 9 mrad off Axis (red) gives better results than 120 GeV 700 KW on Axis (blue) due to less NC background

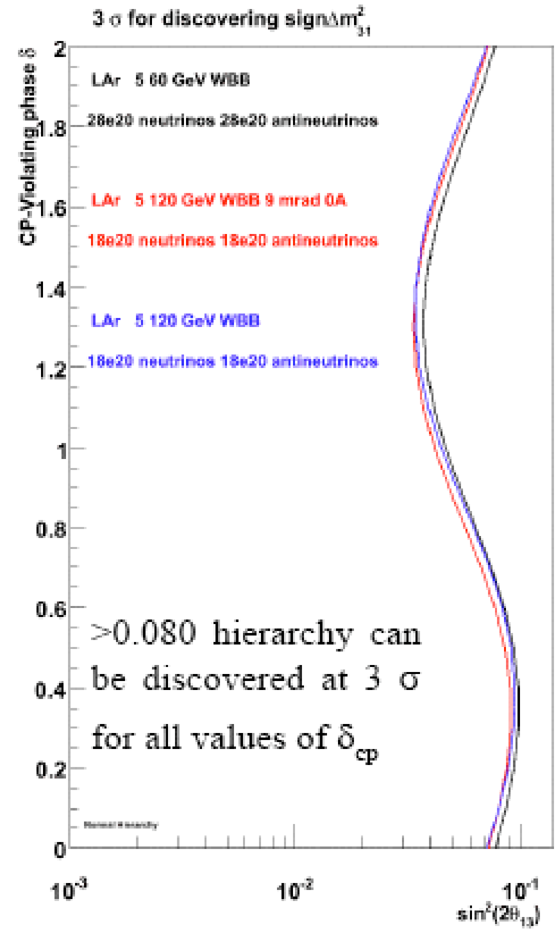
60 GeV 540 KW on axis (black) gives ~ the same results as 120 GeV 700 KW on Axis. 60 GeV 540 KW on axis has slightly less events than 120 GeV 700 KW on axis.

Sensitivities for 5 kt fiducial LAr Detector

NC background = 0.01





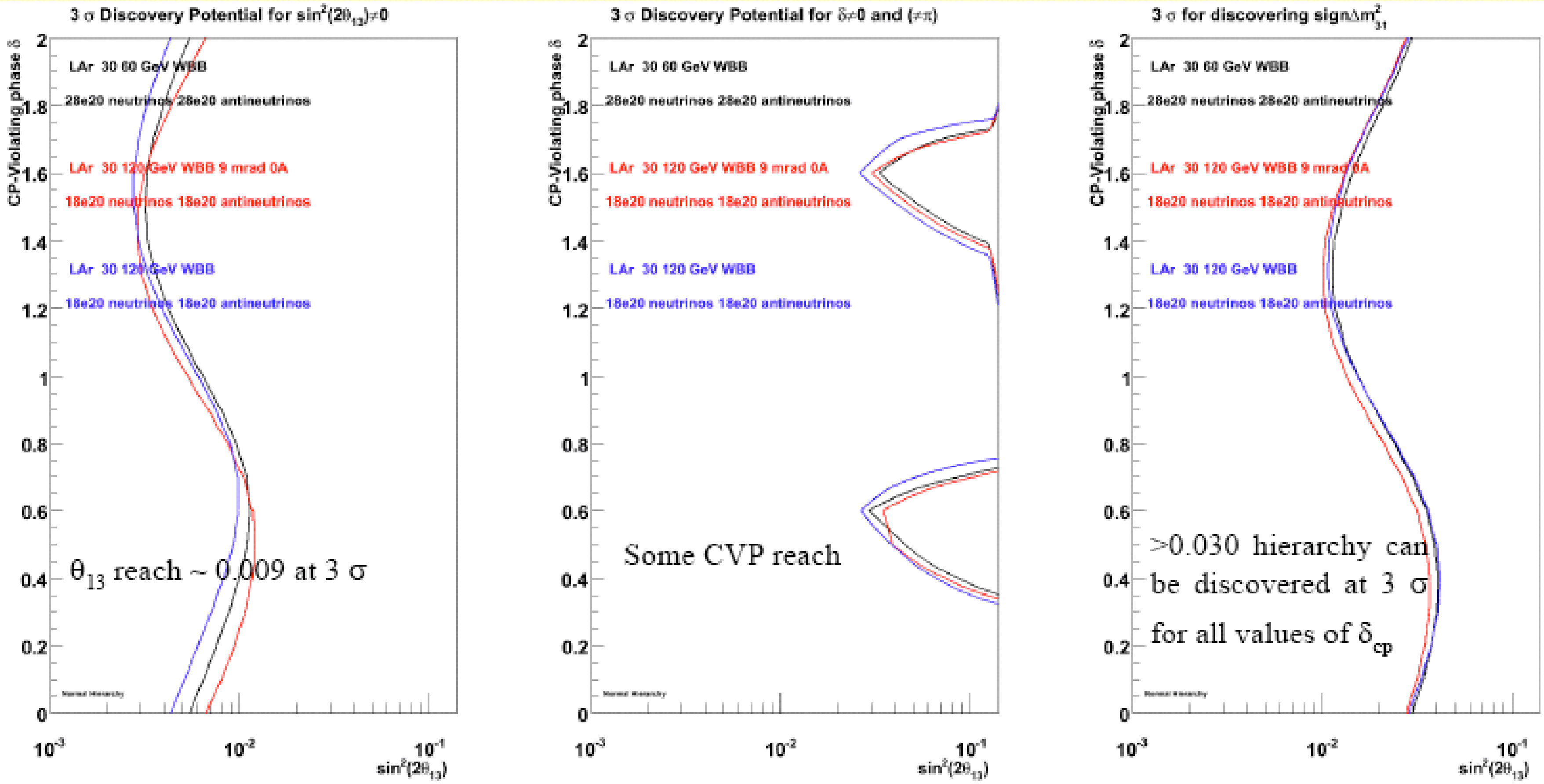


120 GeV 700 KW on Axis (blue) better results than 120 GeV 700 KW 9 mrad off Axis (red) due to more events, NC bkg is small compared to nue signal and does not play important role.

60 GeV 540 KW on axis (black) gives similar results.

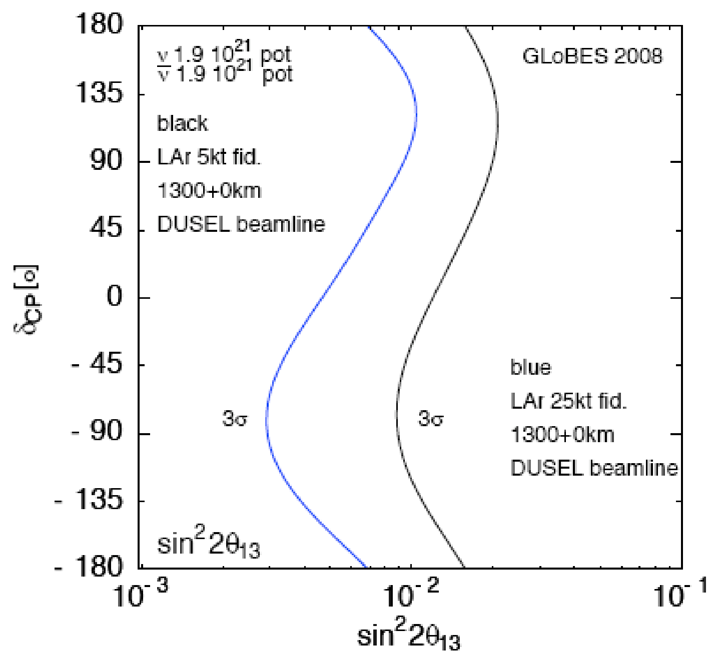
Sensitivities for 30kt fiducial LAr Detector

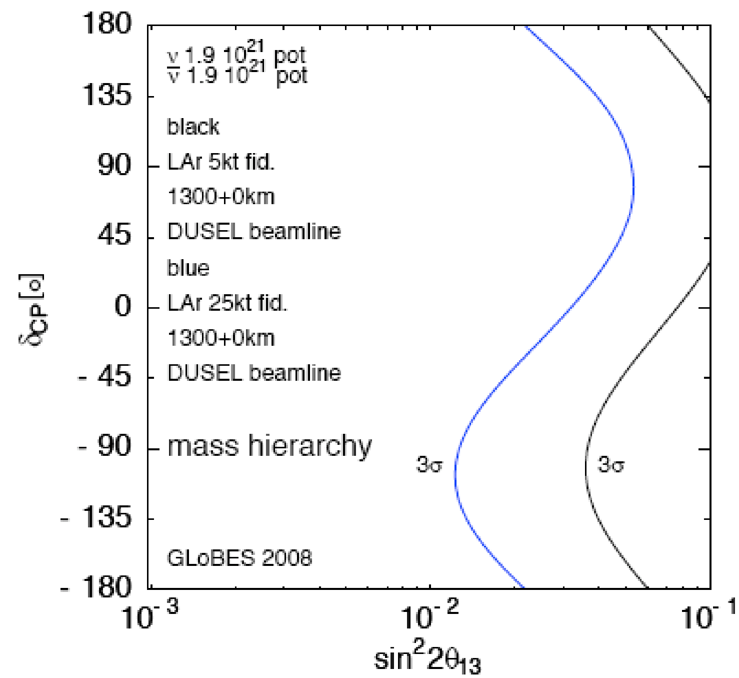
NC background = 0.01



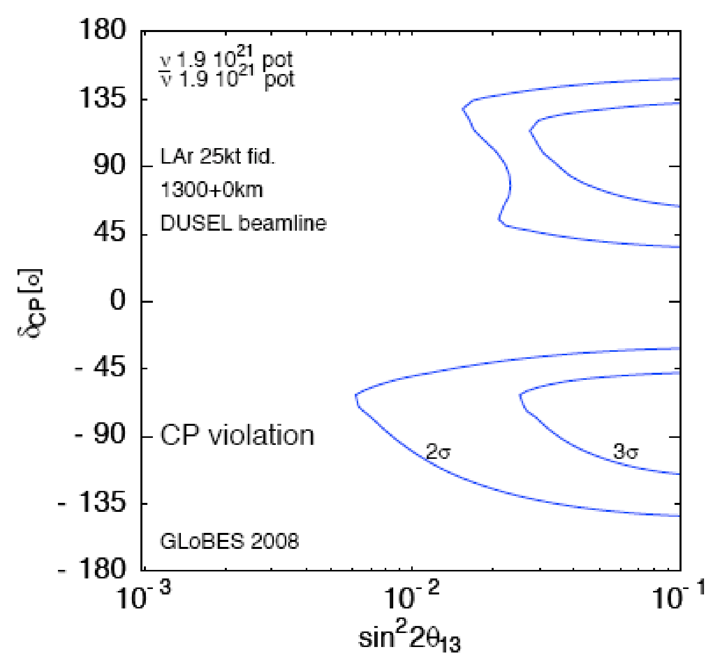
120 GeV 700 KW on Axis (blue) better results than 120 GeV 700 KW 9 mrad off Axis (red) due to more events, NC bkg is small compared to nue signal and does not play important role.

60 GeV 540 KW on axis (black) gives similar results.





Independent calculations for 5 and 25 kT at 1300 km: P. Huber - Globes



Conclusions from studies

- Development of a long baseline experiment : Fermilab to DUSEL has excellent long term scientific reach
- A staged approach looks promising, i.e.
  - 100 kT water
  - 5kT, folllowed by ~25kT LAr
- Planning for a new beam should become part of the Fermilab neutrino strategy

Project Development Strategy

Project Elements

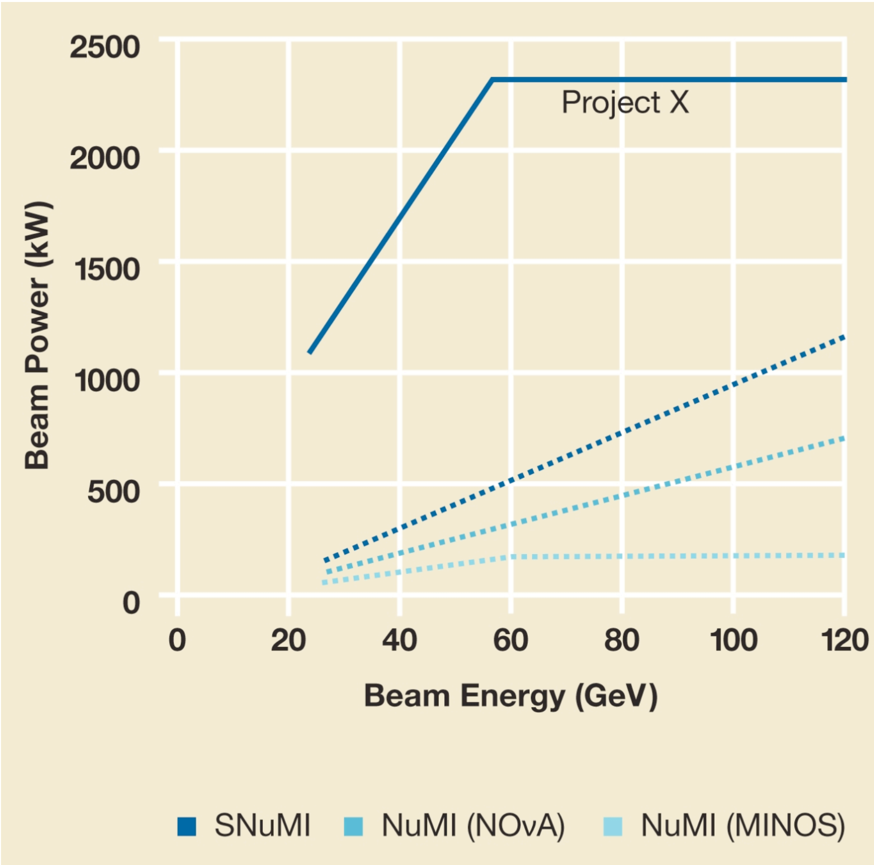
- Protons
- Neutrinos
- Cavern(s)
- Detectors(s)

Project Elements

- Protons
- Neutrinos
- Cavern(s)
- Detectors(s)

Need to be developed as part of the Fermilab long term plan

- 60 -120 GeV protons from the Main Injector fed by Project X



20-40x10^{20} POT/yr

10x10^{20} POT/yr

6x10^{20} POT/yr

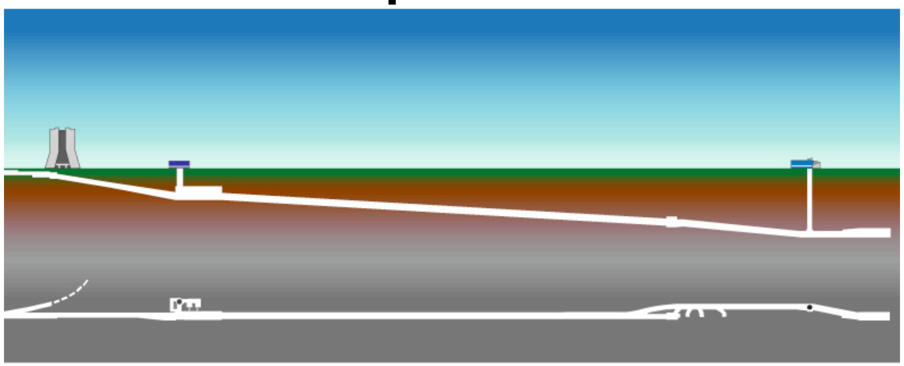
3x10^{20} POT/yr

Recent sensitivity studies are being done for 120x10^{20} POT each ν and $\overline{\nu}$

$$POT(10^{20}) = \frac{1000 \times BeamPower(MW) \times T(10^{7}s)}{1.602 \times E_p(GeV)}$$

A ν beam project ….

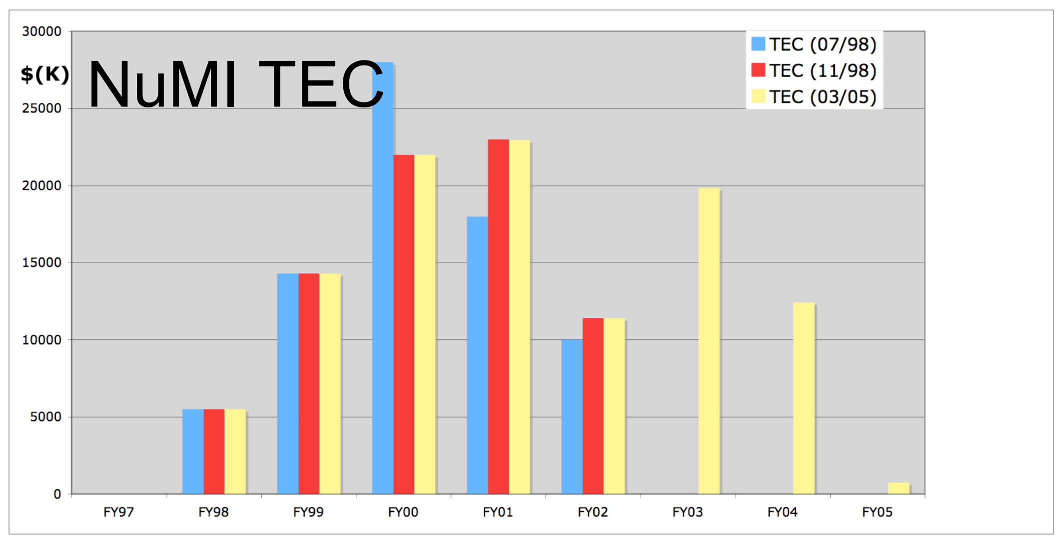
Cost and schedule can be based on our Fermilab underground construction **experience**….



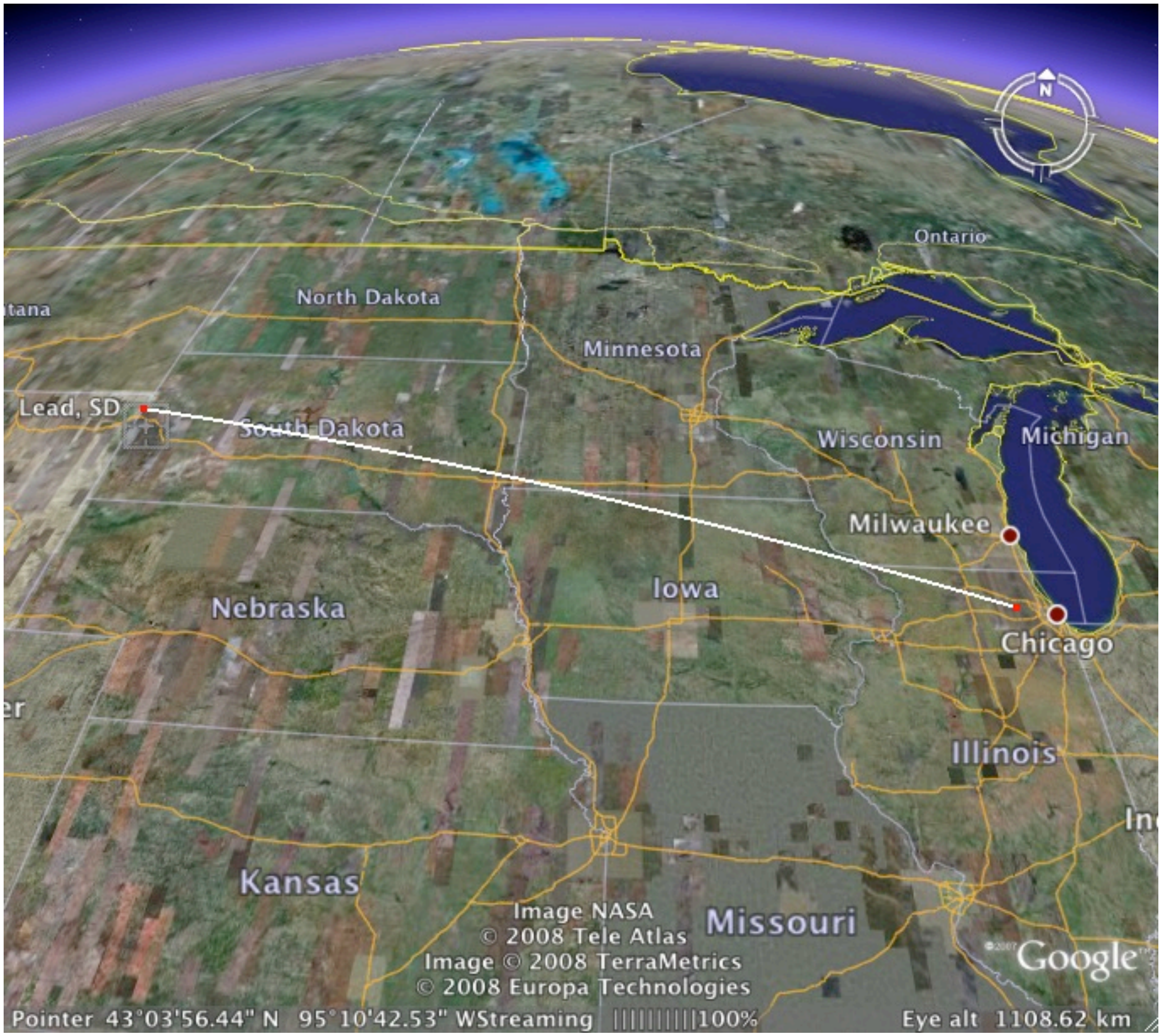
NuMI Civil construction : $75M
NuMI Technical components : $30M
AY$ at project completion 03/05

*2001 re-baseline added $33M to the TEC**
More recent projects have been required to incorporate larger initial contingency

Civil construction included:
2 access shafts
Target & absorber halls
2m diameter x
675m shielded decay tunnel
By-pass tunnel
Near Detector hall



**OPC was only slightly adjusted to match re-baseline schedule*



Ontario
North Dakota
Minnesota
Lead, SD
South Dakota
Wisconsin
Michigan
Milwaukee
Iowa
Nebraska
Chicago
Illinois
Kansas
Missouri
Image NASA
© 2008 Tele Atlas
Image © 2008 TerraMetrics
© 2008 Europa Technologies
Google
Pointer 43°03'56.44" N 95°10'42.53" WStreaming 100%
Eye alt 1108.62 km

Fermilab Planning Initiatives

- Machine/Experiment Interface Working Group
  - Chuck Ankenbrand,
  - Jeffrey Appel,Chair
  - Dixon Bogert
  - Mike Church
  - Dave McGinnis
  - Eric Prebys
  - Gina Rameika
  - Bob Tschirhart

This group will collect the requirements from the experimental Proposals and provide them to the accelerator designers :

XXX protons per year at XXX GeV

with a beam structure of YYY protons per pulse

For a pulse of ZZZ zsec every nsec

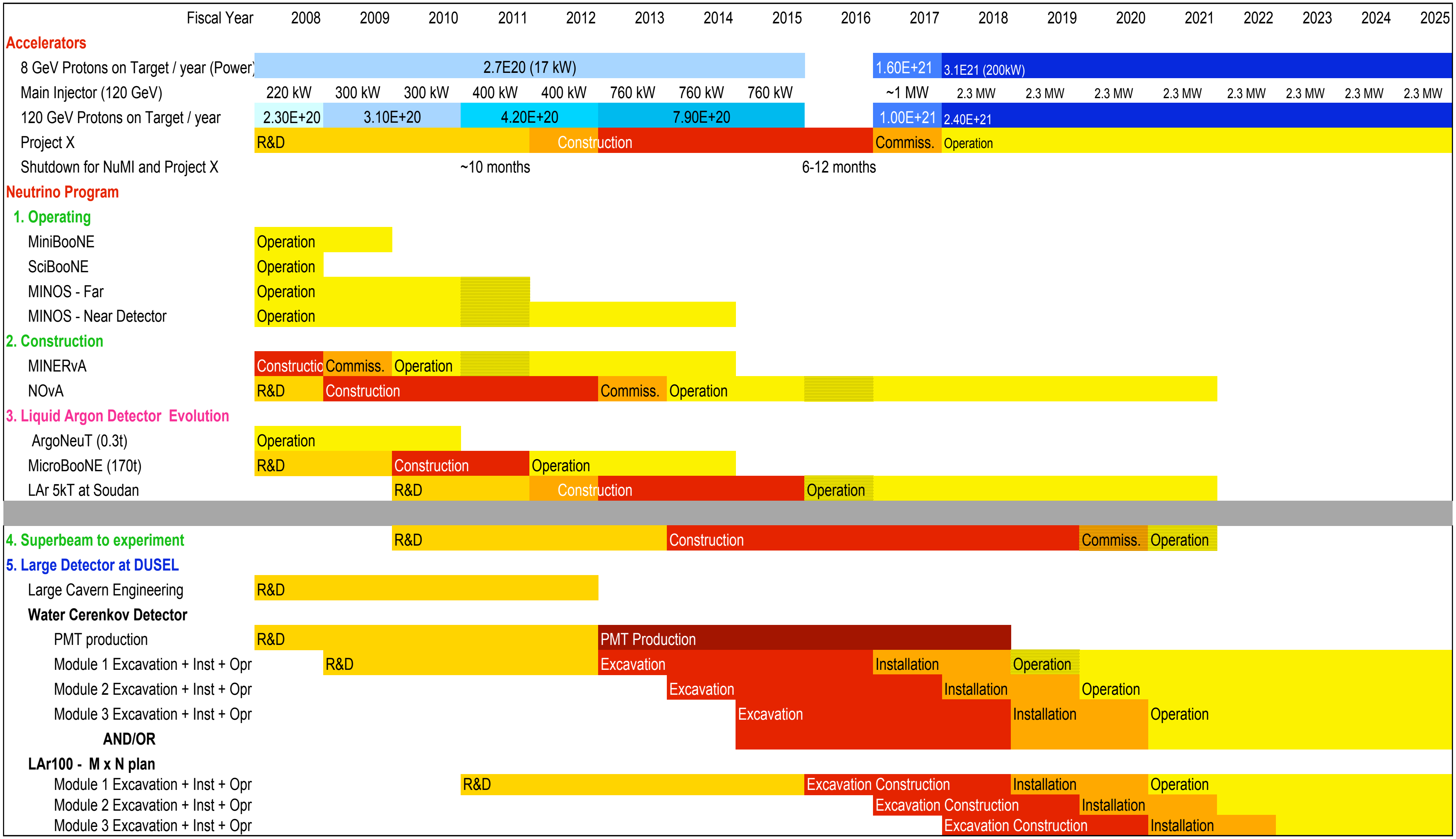
DUSEL Beam Design Working Group

Mike Andrews
Jeffrey Appel, Chair
Dixon Bogert
Sam Childress
Bill Griffing
Nancy Grossman
Dave Harding
Jim Hylen
Vic Kuchler
Chris Laughton
Mike Martens
Elaine McCluskey
Rob Plunkett
Gina Rameika
Gueorgui Velev
Bob Zwaska

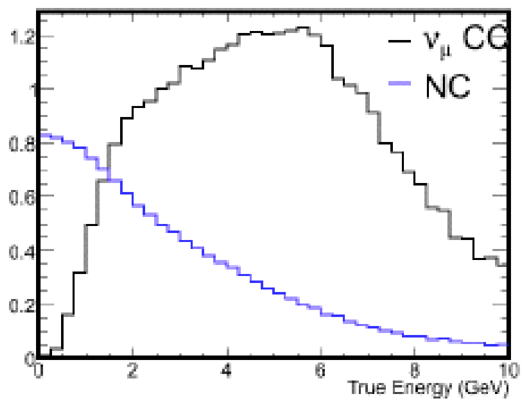
- Physics Requirements
- Civil construction
  - Tunnels and halls
  - Service Buildings and outfitting
- Technical Components
  - Accelerator
  - Primary beam
  - Neutrino Beam
- Management and oversight

This group is just being formed;
Charge to be developed; meant to have lab wide Participation;
Must build on the excellent work done to date, which has been led by the BNL Group;
Will evolve as requirements,scope and schedules are clarified

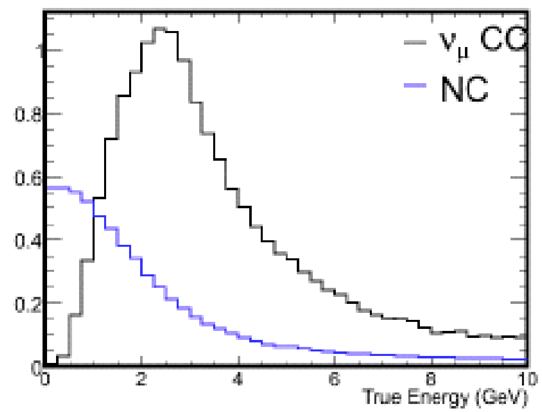
Timeline prepared for P5 (February 2008)



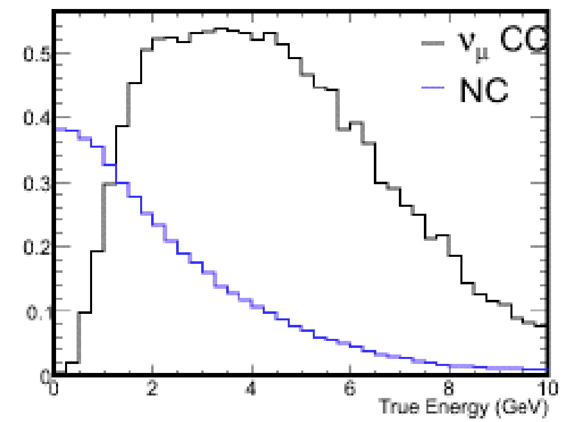
WBB 120 GeV ON AXIS



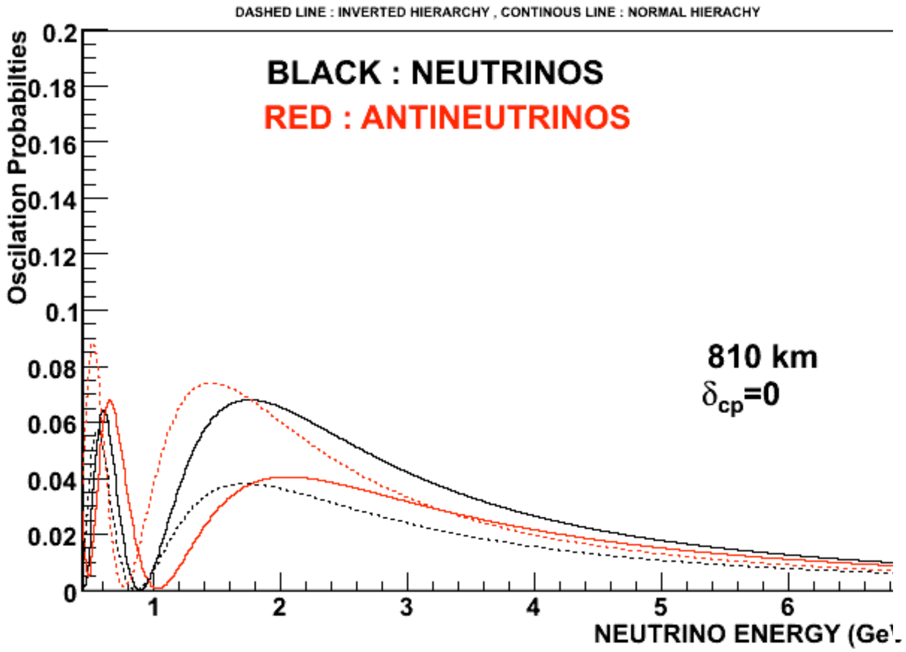
WBB 120 GeV OFF AXIS



WBB 60 GeV ON AXIS



Note : different scale


DASHED LINE : INVERTED HIERARCHY , CONTINOUS LINE : NORMAL HIERACHY
BLACK : NEUTRINOS
RED : ANTINEUTRINOS
810 km
δ_{cp}=0
Oscillation Probabilties
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
1
2
3
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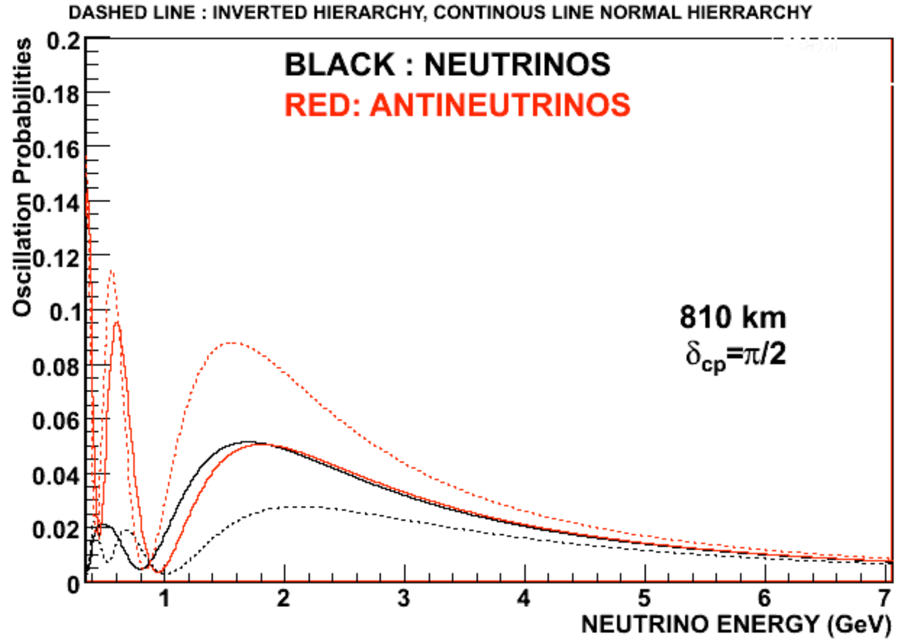
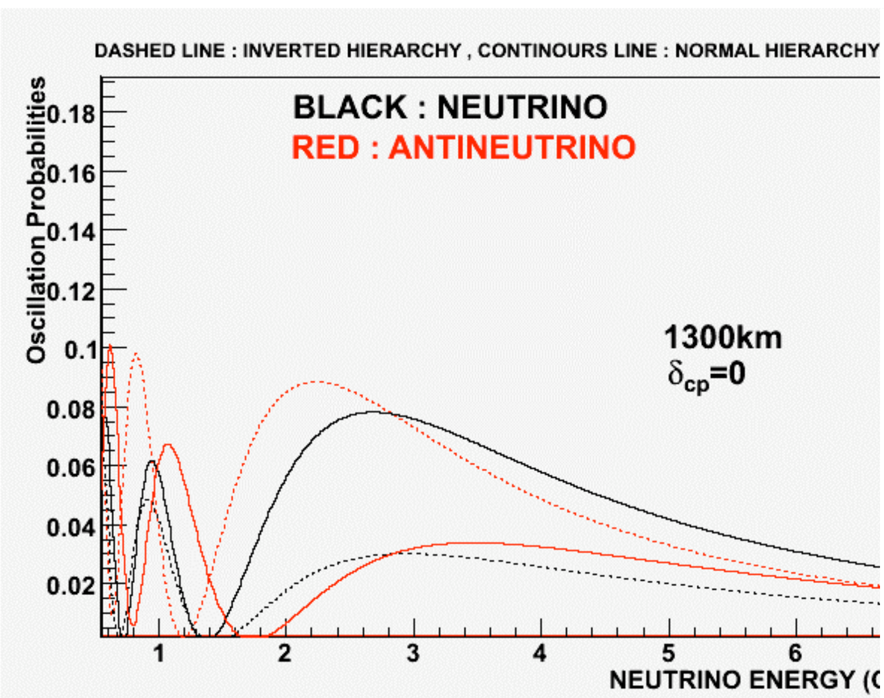
6
NEUTRINO ENERGY (Ge'. ,


DASHED LINE : INVERTED HIERARCHY, CONTINOUS LINE NORMAL HIERRARCHY
BLACK : NEUTRINOS
RED: ANTINEUTRINOS
810 km
$\delta_{cp}=\pi/2$
Oscillation Probabilities
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
1
2
3
4
5
6
7
NEUTRINO ENERGY (GeV)


DASHED LINE : INVERTED HIERARCHY , CONTINOURS LINE : NORMAL HIERARCHY
BLACK : NEUTRINO
RED : ANTINEUTRINO
1300km
δ_{cp}=0
Oscillation Probabilities
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
1
2
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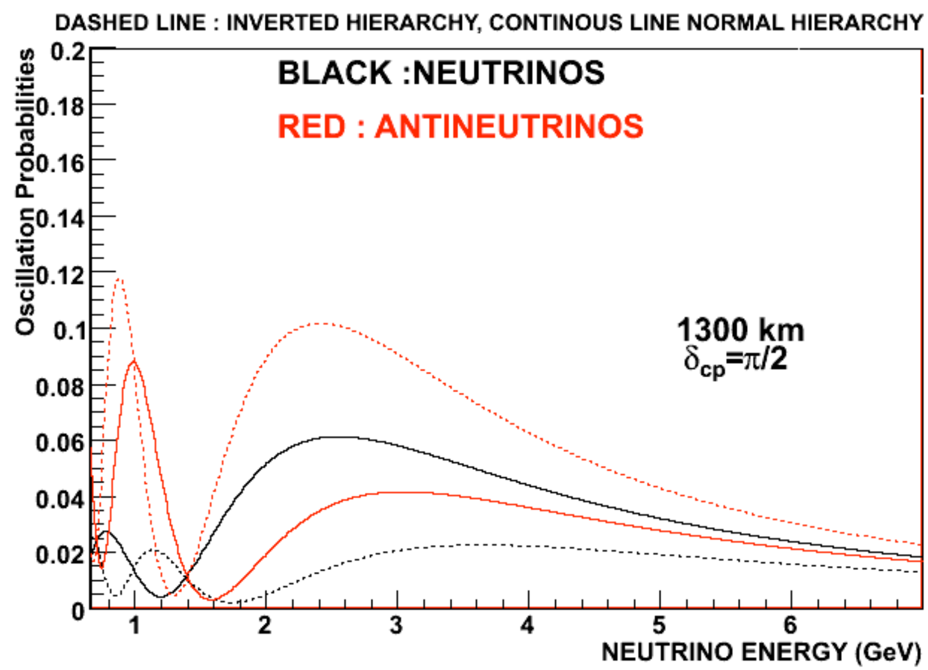
6
NEUTRINO ENERGY (C


DASHED LINE : INVERTED HIERARCHY, CONTINOUS LINE NORMAL HIERARCHY
BLACK :NEUTRINOS
RED : ANTINEUTRINOS
1300 km
$\delta_{cp}=\pi/2$
Oscillation Probabilities
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
1
2
3
4
5
6
NEUTRINO ENERGY (GeV)